NAVAL POSTGRADUATE SCHOOL
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THESIS

VISUALIZATION AND FEASIBILITY ANALYSIS OF THE
GLOBAL OCEAN DATA ASSIMILATION EXPERIMENT,
NORTH ATLANTIC BASIN, SEPTEMBER 2000 TO
MARCH 2001

by

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June 2001

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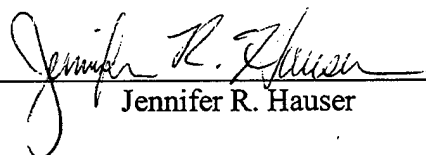Jennifer R. Hauser
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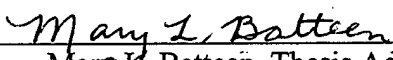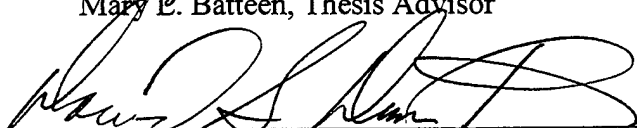## MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY
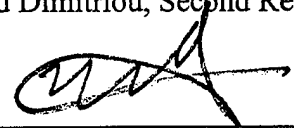
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ABSTRACT

The development of the Global Ocean Data Assimilation Experiment (GODAE), its relationship to the Array for Real-time Geostrophic Oceanography (ARGO) project, and Fleet Numerical Meteorology and Oceanography Center's role in GODAE are discussed in this thesis. The drifting buoys used for data collection are described and the data available is outlined. This thesis analyses GODAE data available from the North Atlantic Ocean, collected in near-real-time from September 1, 2000 through March 8, 2001, in order to evaluate the relative success of the experiment to date and to identify the scope of possibilities for utilizing this data both at present, and once GODAE and ARGO are fully operational. The GODAE project endeavors to be a single database, serving as a collection point for worldwide oceanographic data to be utilized in ocean climate prediction. GODAE does not offer a mechanism for visualization of the data available. This thesis analyzes the data presently available through graphic representation. Visualization products include: float trajectories, temperature (T) and salinity (S) profiles, T-S diagrams, mixed layer depths and observed temperature compared to temperature climatology.

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I. INTRODUCTION

Meteorologists have the luxury of studying a medium that is relatively easy to access, observe, and sample. The earth's atmosphere is well traveled by both manned and unmanned machinery, viewable and measurable from the thermosphere to the troposphere, and inundated with billions of observation stations. Atmospheric data is readily available to meteorologists in real-time, providing them with the tools required to predict the weather. The job of an oceanographer is much more difficult. The Global Ocean Data Assimilation Experiment, or, GODAE, was developed to provide oceanographers with near-real-time global oceanographic data that can be utilized as raw data, or ingested into global oceanographic prediction models. It employs a comprehensive and integrated approach to gathering ocean data. GODAE will be a mechanism to provide regular and complete descriptions of the temperature, salinity and velocity structures of the ocean. The potential GODAE has is immeasurable, it will in essence, provide oceanographers with the tools necessary to forecast and predict the "weather of the ocean." Data gathered from GODAE will assist oceanographers in the exploration of ocean state estimation, global weather and climate influencing phenomena such as El Niño and ocean basin oscillations. The data collected will be useful for seasonal-to-decadal climate forecasting and analyses, operational oceanography and oceanographic research, naval applications, marine safety, fisheries, the offshore industry and the management of shelf and coastal areas (IGST, 2000). The ocean prediction knowledge that GODAE will facilitate will be beneficial to international society, research of the marine environment, climate, and climate change.

The development of GODAE was driven by both need and opportunity. There is a high user demand for global ocean data and a well supported global ocean observing system. The opportunity and technology to observe the ocean through remote sensing and *in situ* observations

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is finally available through increased scientific knowledge. Ocean prediction models have evolved, and now have the capability to ingest more numerous and varied data points and to allow air-ocean coupling.

The development of the GODAE project, its relationship to the ARGO project, and Fleet Numerical Meteorology and Oceanography Center's role in GODAE are discussed in this thesis. The buoys used for data collection are described and the data available is outlined. This thesis analyses the North Atlantic Ocean data collected in near-real-time from 1 September 2000 through 8 March 2001, in order to evaluate the success of the experiment to date, to identify the scope of possibilities for utilizing this data, and to examine its effectiveness in regional oceanographic studies. Visualization of float trajectories, temperature (T) and salinity (S) profiles, T-S diagrams, mixed layer depths and observed temperature compared to temperature climatology are included. Recommendations for future research are made and a summary of conclusions is presented.

II.   THE GODAE PROJECT

A.   THE DEVELOPMENT OF GODAE

The oceanographic community has a need for establishing a global real-time ocean analysis and prediction system, but has not yet been able to successfully do so. The Ocean Observation Panel for Climate (OOPC) proposed the Global Ocean Data Assimilation Experiment (GODAE) in 1997 as a means of establishing a process for long-term data collection and the assimilation of that data into global oceanographic models.

1.   The Vision of GODAE

The vision of GODAE is:

A global system of observations, communications, modeling and assimilation, that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community (IGST, 2000).

GODAE hopes to demonstrate the practicality and feasibility of routine, real-time global ocean data assimilation and prediction. Demonstration of these capabilities is essential to the realization of a permanent, global ocean observing network and prediction system with a global domain of components that is capable of delivering products in a timely manner. GODAE is not a research program, but rather a multi-purpose operational experiment, aiming to deliver useful oceanographic products that have been derived from a global ocean data set and assimilated into a model in order to extract greater benefit from the data collected and to deliver these products in time to be valuable for ocean prediction (Smith, 2).

2.   Opportunity and Need

GODAE was developed due to both the need and opportunity for global ocean prediction. User demand for global ocean data and a well-supported global ocean observing system is high.

The requirement for global ocean measurements has been growing for several decades. GODAE was proposed in 1997 because at this time, the means to achieve this global ocean measuring requirement were available through the advances of science and technology.

Ocean characteristics can now be observed and measured through remote sensing and *in situ* observations. The development of the autonomous profiling float provides the mechanism for taking these measurements, as well as the means for global distribution (Smith, 1998).

Data assimilation and prediction models have also advanced, giving modelers the capability to effectively "couple" atmospheric and oceanographic models, emphasizing the air-ocean interface that is critical to weather prediction (Roemmich, 2000).

A global satellite observing system is currently in place and functioning. Satellite altimeters can now measure the height of the sea surface with tremendous precision. These progressions in science and technology have provided GODAE with the tools required to achieve its mission of accurately depicting and predicting the state of the ocean.

The need for the GODAE project is driven by user demand for global ocean products over a wide range of time and space scales. There is also a need for a global infrastructure of ocean observing systems in order for ocean science to develop further. Regular ocean analyses are required as the foundation for future scientific research and development. GODAE will serve as a springboard for a future robust, routine, permanent and well-supported network of ocean observations (IGST, 2000).

The opportunities for the development of GODAE include the evolution of remote and direct observation systems that make large-scale, real-time observations possible. Scientific advances in global ocean modeling and data assimilations in fine time and space scales offer

further opportunities for GODAE. The oceanographic community is eager to promote and implement an integrated global observing system (IGST, 2000).

3. Ocean Dynamics and GODAE

The ocean is the major reservoir of the earth's water, and heat. Ocean dynamics and thermodynamics contribute to global climate change through heat redistribution and the storing of climatically active gases. The dynamics of the ocean and atmosphere are not mutually exclusive. The exchanges that occur at the air-sea interface are vital to the understanding and prediction of both atmospheric and oceanographic conditions. The exchange of heat, moisture and momentum between the ocean and atmosphere is what causes weather phenomena. Changes in the atmosphere occur at a much faster rate than changes in the ocean. Squalls come and go within minutes. Tornadoes dissipate just as quickly as they are formed. The lifespan of a hurricane or tropical depression is generally days. Ocean dynamics, however, are much slower. Oceans store and transfer vast amounts of heat. Over seasons and decades, this transfer of heat can be seen in global patterns of rainfall, winds, storms and other changes in atmospheric circulation (Wilson, 2000). Global measurements of oceanic heat storage and transport are necessary for establishing a climate observing system. Further progress in understanding and predicting climate variability depends on a global observation system. (Roemmich, 2000) Specifically, equatorial ocean dynamics are important in the study and prediction of the El Niño phenomenon.

4. GODAE and El Niño

In the event of an El Niño, a large mass of warm water moves from the western Pacific Ocean toward the east, accumulating off of the west coast of North and South America. The prevailing trade winds weaken, and change global atmospheric circulation patterns. A La Niña

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event has the opposite effect, cooling the eastern Pacific. These changes result in global weather transformations. The intense El Niño of 1997 resulted in catastrophic weather changes. It created droughts and widespread fires in Australia. Flooding occurred in the usually dry regions of Peru and Ecuador. Unseasonably intense storms restructured the beaches of California. Ocean temperature changes resulted in the loss of massive amounts of fish, and therefore massive amounts of the birds dependent on these fishes. The 1997 El Niño led to thousands of deaths and an estimated $13 billion in damage.

The aftermath of the 1997 El Niño inspired a focus in studying global ocean changes. The El Niño Southern Oscillation (ENSO) Observing System was put into place to track real-time observations in the hopes of forecasting the onset and duration of future El Niño events. GODAE will further the efforts of ENSO, providing the framework necessary for global ocean prediction, particularly of events such as El Niño.

B. THE OBJECTIVES OF GODAE

The objective of GODAE is to provide real-time global ocean data assimilation through regular depictions of ocean elements including temperature, salinity, currents and sea level at high temporal and spatial resolutions. As outlined by the International GODAE Steering Team (IGST), the specific aims are to: coordinate and foster a more efficient, responsive and sustainable system for data assembly, quality control and access; improve public access to and awareness of the many marine services products, both operational and research that are available; foster the development of a shared "Common" of ocean information and tools for the production of improved ocean products; foster the production and analysis of improved ocean service products; undertake experiments to assess the utility of various ocean data streams for different applications, and guide the evolution of a global ocean observing system, until the system and

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tools are able to produce ocean service products that meet the needs of the GODAE sponsors (IGST, 2000).

The focus of GODAE is on global products that will efficiently fulfill the requirements of a broad spectrum of local, regional and global users. The emergence of new applications and users will drive the development of new and improved operational products. GODAE products will be tailored to both operational and research applications. Operational applications are user-driven, while research applications are science-driven. Both types of customers are interdependent. As the products are developed to meet needs on both sides, valuable overlaps will occur, increasing overall utility. These overlaps will improve estimates of fields such as climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences and location and rate of ventilation. Intersections in data will identify errors and allow forcing fields and models to be improved (IGST, 2000).

1. Global Ocean Prediction

GODAE was developed as an instrument to monitor and forecast the behavior of the ocean and implement seasonal prediction and climate forecasting systems. Further understanding of prediction capabilities for the behavior of the ocean are crucial to the development of economic activities on the open ocean and along the world's coastlines. GODAE hopes to make ocean monitoring and prediction as routine as atmospheric monitoring and weather prediction. GODAE will implement and develop and sustain a long-term network of global ocean measurements from both direct and remote sensing systems. Descriptions of the ocean state will be regularly obtained through the ingest of observations into ocean model predictions. Ocean prediction models allow data to be assimilated and integrated in a manner that is consistent with current use of ocean dynamics and physics (IGST, 2000).

GODAE intends to provide analyses and forecasts of the mixed-layer out to three-five days, the mesoscale ocean, out to 10-20 days and seasonal and longer-term variability. GODAE also hopes to improve the accuracy and value of open ocean analyses and forecasts through improvement of estimates of currents and their variability along the shelf break and of the waters on the continental shelf. GODAE strives for real-time, immediate product delivery. Products will have high precision, eddy resolving operational oceanography and near-real time climate applications (IGST, 2000).

2.   The Results of GODAE

A sustained global ocean observing network and operational oceanographic systems will be the legacy of GODAE. The investment of the GODAE project balances the cost of long-term deliverables with the short-term economic and social returns. The IGST outlines the outcomes of GODAE as: an improved capacity for prediction for coastal, shelf and regional subsystems through the provision of suitable oceanic initial and boundary conditions; better initial conditions for climate predictions and analyses for validation of climate simulations; improved open ocean nowcasts and forecasts; integrated analyses or reanalyses for research programs, such as CLIVAR; description of the ocean circulation and physics upon which more specialized systems, such as ecosystem models, can be developed and tested; a foundation for hypothesis testing, process studies and further experimentation, much as is commonplace in numerical weather prediction today; improved availability and utility of ocean data; a methodology for systematic handling, quality control and consistent scientific interpretation (analysis) of special data sets such as those from process studies and arising from incidental exploration; assessments of the observing system and of the utility of new ocean data sets (e.g., new altimetric missions, sea surface salinity from satellites); model testing and improvement; a viable, long-term observing

system (GOOS); and development of an enhanced user base and suite of applications (IGST, 2000). Full achievement of GODAE depends on the real-time availability of remotely sensed and *in situ* observations, data processing, management and delivery, global state estimation and diverse applications in modeling (IGST, 2000).

C.   THE ORGANIZATION OF GODAE

The organization of GODAE is based on facilitation by project Patrons and implementation by Partners associated with the project. GODAE Patrons include agencies and groups that provide resources for GODAE activities, supervise program management and enhance the capacity of the GODAE Common. GODAE Patrons are tasked with marketing GODAE, its value and products, both nationally and internationally. Patrons will suggest a focus for national participation and solicit and coordinate resources in support of GODAE. GODAE Patrons will also advise the International GODAE Steering Team with regard to resources and international collaboration.

An International GODAE Steering Team, IGST, was appointed to develop the GODAE project. The IGST will promote both regional and global demonstrations of global ocean data assimilation. The scientific basis for changes in the ocean observing system, data assimilation algorithms and ocean models will be provided by the IGST. The IGST will evaluate and implement scientific and technical developments into GODAE. Members of the IGST will liaison with interested customers worldwide. They will nurture communication and collaboration between GODAE product developers and end-use customers. The IGST will make recommendations for future operational global ocean data assimilation projects.

A GODAE Office was established by the GODAE Patrons to provide management support and coordinate all GODAE efforts. It is located in Melbourne, Australia, at the

Australian Bureau of Meteorology. The GODAE Office directly supports the GODAE IGST and the ARGO project. The office staff works to promote international coordination of research and operational programs related to the GODAE effort. GODAE publications and reports are made available through this office and it hosts the GODAE home page. The GODAE Office works with the Patrons to advertise the benefits and objectives of GODAE to operational and research communities.

The GODAE Executive is comprised of the Patron Chair, the IGST Chair and the Office Director. The GODAE Executive advises the GODAE organization and strives to resolve issues as they arise (IGST, 2000).

1. The GODAE Common

The IGST has determined one of the guiding principles of GODAE to be the institution of a GODAE "Common." This doctrine is to be shared by all GODAE partners, and includes: assimilation products from existing national research and operational activities; GODAE-specific data products developed through existing facilities and new efforts; infrastructure, such as data and product servers, assembled specifically for GODAE, and the knowledge base accumulated through joint development, intercomparison experiments, and other GODAE collaborations.

Although GODAE has a scientific basis and a strategy that is based on scientific "best-practice," it is not a research experiment. It is a practical demonstration of feasibility and utility and of near-real-time, routine global data assimilation. The strategy established by the IGST includes: the GODAE Common must be built on the paradigm of open, readily accessible, routine data and products; GODAE will build on existing scientific and operational capabilities where practicable, capitalizing on the developments and successes of WOCE and TOGA, and engender an effective partnership between the operational and research communities; GODAE

will build on and advance national and international operational activities relating to ocean data assimilation; the global assimilation products for the operational phase of GODAE will be the synthesis of multi-variate *in situ* and satellite data through global ocean models, for a diverse set of applications; GODAE will focus effort on the scientific and technical development of the core information system; GODAE will develop value-added and specialist products through linkages and partnerships to other communities, and GODAE will leverage off many operational and research efforts, from regional to global perspectives. The guiding principle for global and/or regional models and assimilation systems is that these activities should foster the development of the core systems of the GODAE Common; ocean state estimation tools will provide a framework for quantifying the contributions from different data sources and new data types (such as remotely sensed salinity), thus improving the design and efficiency of the observing system; GODAE will progressively test and, as appropriate, adopt new technologies and scientific methods, and GODAE must lay the foundation for a long-term sustained ocean observing system and a sustained routine ocean product line (IGST, 2000).

2.   Benefits and Users

The IGST identifies GODAE benefits and users as: short-term environmental data for public service and commercial use (for profit, increased efficiency or improved safety of operation); medium to long-term environmental data and statistics for engineering and designing for extreme conditions; environmental management information: real-time and climate information on the natural environment; climate and seasonal variability and forecasts; and long-term climate information including trends and climate change (IGST, 2000).

3. Collaborating Institutions

GODAE is a project of the OOPC, and a pilot project of the Global Ocean Observing System (GOOS). The Global Climate Observing System (GCOS), GOOS, and the World Climate Research Program (WCRP), jointly sponsor the OOPC. The Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) also supports GODAE. Participating countries include: Japan, the United Kingdom, Norway, France, Australia, Brazil, Germany and the United States. Specific patrons include: European Meteorological Satellites (EUMETSAT), the National Oceanographic Atmospheric Association (NOAA), the Japan Marine Science and Technology Center (JAMSTEC), the National Aeronautics and Space Administration (NASA), the French Space Agency (CNES), the United Kingdom Meteorology Office, the Bureau of Meteorology, and the National Space Development Agency of Japan (NASDA).

4. Areas of Focus

Over 128 different countries, concentrated among Australia, Canada, France, Germany, Japan, the Republic of Korea, the United Kingdom and the United States, have purchased ARGO floats. In the United States, ARGO floats are being tracked by the Scripps Institution of Oceanography, SIO, in La Jolla, California, the University of Washington, UW, in Seattle and Woods Hole Oceanographic Institution, WHOI in Massachusetts.

5. Phases

GODAE is comprised of four planned phases.

Phase I, Concept Development, was completed in 1997. This phase included the draft proposal review and endorsements. The objectives during this phase were to define the scope of

GODAE, advertise the experiment, develop international participation and to establish an organizational structure. The ARGO project was also initiated during this phase.

Phase II, the Development Phase, was completed during 1998 and 1999. Phase II included the development of an implementation strategy and an assessment of GODAE capabilities. Interested groups, individuals and agencies were identified and integrated into the planning process and an infrastructure was established. GODAE components were tested through prototype systems and pilot projects.

GODAE is currently in Phase III, the Demonstration Phase, to be completed in 2002. Phase III includes the testing of subcomponents and regional and pilot experiments. The true viability of GODAE will be realized during this phase. Integrated systems will be distributed to the set GODAE partners and products will begin to be available. The GODAE system will be improved during this phase, improving methodologies and products as new users are attracted. The value and effectiveness of the components and products of GODAE will also be assessed.

Phase IV is the Consolidation and Transition phase, planned from 2003-2005, with an anticipated extension to 2007. GODAE will be fully operational during this phase. The time frame of Phase IV allows set satellite schedules to complement the culmination of the World Ocean Circulation Experiment (WOCE). Accumulated GODAE technology will be made operational and the framework will be in place for future GODAE endeavors (IGST, 2000).

D.   GODAE DATA

Atmospheric forcing, wind stress, wind speed, air temperature, specific humidity and precipitation are among the observational and data requirements for GODAE. Other requirements include sea-ice coverage data and data for assimilation such as altimetry and sea

surface temperature observations. Validation data such as hydrography, and supplementary data sets, including climatology and bathymetry are also necessary. GODAE will also utilize data from Numerical Weather Prediction (NWP) centers. Data sets must be accurate, timely and immediately functional. The GODAE approach is strengthened by similarities in the data available as well as in user requirements.

Remotely sensed sea surface temperature, topography and winds will be provided in near-real-time, long-term, synoptic, and global estimates. Sea surface temperature (SST) data in near-real-time is necessary for assimilation into ocean models. SST data will allow models to resolve finer scale features, such as oceanic fronts and will contribute to the boundaries of thermal fields. Sea surface topography data will be collected from several altimeters in order to constrain the ocean model mesoscale circulation and provide useful information on the surface velocity field. Geoid models are also required to derive precise topography and currents from altimeters. *In situ* data will verify altimetric data, providing a baseline for calibration and a method for monitoring altimeter performance. Scatterometer data from both morning and afternoon polar orbits will provide the required wind vector measurements. GODAE will also employ sea ice products, such as sea ice extent and sea ice concentration, as well as the penetration of light in the ocean, or ocean color data. *In situ* data will be provided to GODAE through the ENSO observing system, ARGO, the Ship-of-Opportunity Programme (SOOP) Expendable Bathythermograph (XBT) data, drifters, surface moorings, ships and time series stations. Mesoscale operational applications will be carried out using high resolution XBT data and currents derived from drifters and floats. The *in situ* observing system will be able to determine mesoscale variability statistics such as space and time scales, vertical structure and the

contribution of barotropic and baroclinic components. In order to test, validate and reanalyze data sets, GODAE will require both real-time and delayed mode data (IGST, 2000).

1. Global Ocean Prediction Models

A dynamical ocean prediction model provides the capability to extrapolate information, enable archived data to be used in present analyses and to use present data as a basis for forecasts. Practical ocean models will have resolution fine enough to replicate eddies, the meandering of surface currents, oceanic fronts, and the structure of the upper ocean. Models with coastal applications will require accurate sea level information, including tidal and surface pressure forcing. Upper ocean structure is utilized in seasonal-to-interannual climate forecasts. Modeling applications in biogeochemistry also require upper ocean characteristics. All global ocean models require considerable computational resources. According to the IGST, GODAE models will include: eddy resolution and global domain; high vertical resolution; advanced upper ocean physics; high-performance numerical code and algorithms; and efficient interfaces to other models (IGST, 2000). Model validation will occur through model-model and model-data comparison. GODAE plans to use several different approaches to modeling in order to fill in sections of missing data and test the reliability of ocean state estimates, initial conditions and forecasts (IGST, 2000).

In situ measurements and surface data collected through remote sensing are often reported as incomplete data sets. State estimation tools can be used to interpret, interpolate and extrapolate this missing data. State estimation tools can also be used to derive fields that cannot be measured directly. The ingest of forecast and observation error statistics into assimilation analyses provides more realistic estimates of the ocean state and better short-range forecasts than either the model or data alone could produce (IGST, 2000).

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2. GODAE Products

The products featured by GODAE as identified by the IGST will be: operational global mesoscale nowcast and short-range upper ocean forecast fields; analyses for initializing and testing of seasonal-to-interannual forecasts and other climate forecasts; and global, consistent four-dimensional re-analyses of temperature, salinity and flow fields (IGST, 2000). The outcome of GODAE will be significant improvement in the detail, quality, timeliness, availability and usefulness of the above products.

The GODAE project expects to develop more coherent, better organized, more widely available and more useful oceanographic data sets. Data sets will be developed more effectively and made available to all GODAE customers. Data quality and utility will also be improved through the provision of quality data that can be manipulated into a wide variety of products and processed data. Differences in incoming data noted from one day to the next can be used to monitor the quality of incoming data and to emphasize the data with the greatest impact to the model output.

The IGST identifies unique GODAE products as: global, consistent analyses, available regularly and routinely; increased attention given to end applications, e.g. nesting with a very high-resolution regional model; a hierarchy of products at different resolution, with assessment of the impact of resolution; products resulting from models with different tolerance of errors; and a hierarchy of products of differing complexity and sophistication, e.g. with/without detailed representation of the mixed layer (IGST, 2000). Short-range ocean prediction, producing a global ocean forecast several weeks out and a support of coupled air-sea prediction and surface wind waves are among the main focus of GODAE. The IGST assembled modeling and assimilation groups to focus on the synthesis of data into global ocean prediction models.

Operational global high-resolution nowcast, short-range forecast fields and global analyses for climate applications will be the main GODAE products (IGST, 2000).

The continued revision and improvement of analyses will be achieved through either re-analysis or intercomparison processes. The characterization of errors and uncertainties in outputs will be recognized by GODAE. Error statistics will be confirmed with the actual data and through GODAE user feedback. User feedback is an important part of the GODAE project's dedicated improvement cycle. Recommendations for the best available sources of information will be made available. A product and standards improvement cycle will be developed in order to continually upgrade the GODAE Product Suite, ensuring that customers have access to the best quality data, as well as the products that best meet their needs.

3.   Operational Components

According to the IGST, operational components of the GODAE project include: measurement networks (*in situ* and remotely sensed); telecommunications and data assembly centers; data servers; modeling and assimilation groups or centers; product servers and delivery systems; computational resources; application centers or service providers, and end users (IGST, 2000). Feedback and communication between these components is essential to the success of GODAE.

Specialized data assembly centers will be responsible for the production of GODAE data sets, including, profiling floats, altimetry, NWP products and SST. Production will include data collection, quality control, and the manipulation of data sets into higher-level data in an easy to assimilate format. Data centers will not be a part of the GODAE Common, but will participate through the contribution of these products and collaboration with the GODAE Assimilation Centers. In order for data flow between Assimilation Centers to be reliable and unimpeded by

other data types, GODAE-specific data servers have been established. GODAE data server providers will monitor this flow of data (IGST, 2000). The United States Navy's Fleet Numerical Meteorology and Oceanography Center in Monterey, California will host the U.S. data server, termed "USGODAE."

E. FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER

Fleet Numerical Meteorology and Oceanography Center (Fleet Numerical) is located in Monterey, California. Fleet Numerical is under the direction of the United States Navy's Commander, Naval Meteorology and Oceanography Command (CNMOC). Its mission is to collect, interpret, and apply global atmospheric and oceanographic data and information in support of strategic and tactical warfare and peacekeeping missions. To better support its mission, Fleet Numerical will maintain an active role in the collection and redistribution of global ocean data. This will be achieved in part by hosting the USGODAE server at Fleet Numerical.

Data collected by the individual ARGO floats will be transmitted to a satellite every 10 days to the USGODAE Server, hosted by the Fleet Numerical. Fleet Numerical was chosen to host the USGODAE server because of its tremendous supercomputing capabilities and the contribution of the Navy Oceanographic Global Atmospheric Prediction model NOGAPS to assimilate GODAE data into. This arrangement also involves the U.S. Navy with GODAE at an early stage, providing the Navy with useful operational oceanographic products.

1. The USGODAE Server

The purpose of the data server is to provide a wide variety of products and data to U.S. GODAE participants and to provide access to U.S. and international GODAE assimilation

products. There are four main data management functions of the USGODAE server: to provide and maintain a consistent framework for users to locate and access the documentation associated with each data and product source; the conversion of external data formats to a small collection of common formats; to provide users with selectable subsets of data and products; and to utilize on-line comparison of data and products, to include graphical overlaying and differencing, and other existing technologies as much as possible. Developing and maintaining multiple sources to a variety of data and products is also an important function of the USGODAE data server (Dimitriou, 2000).

The USGODAE server contains: real-time and historical oceanographic observations; real-time and historical surface atmospheric forcing fields to drive GODAE ocean models from Fleet Numerical and the National Center for Environmental Prediction (NCEP) of NOAA; a full suite of real-time surface and upper-air fields from NOGAPS to meet the needs of the Cooperative Opportunity for NCEP Data Using Internet data distribution Technology (CONDUIT), program; selected U.S. Navy operational oceanographic products; ancillary data sets useful for GODAE modeling efforts, including ocean climatology and bathymetry; and GODAE demonstration products from various GODAE modeling groups (Dimitriou, 2000).

Implementation and maintenance of the USGODAE server at Fleet Numerical will entail the following functions: identify and assemble the various products and data sets; create programs and scripts for automated data processing projects; combine high-level programs with automated File Transfer Protocol (FTP) and web interfaces; maintain web site and data distribution systems for research projects; monitor system storage and data set usage and develop archive functions for USGODAE data and products; employ existing off-the-shelf software and technologies for browsing, visualization, searching and downloading; provide user controllable

subsets and reformatting capabilities; and monitor system usage and ensure validity of web links (Dimitriou, 2000).

The Fleet Numerical system will support the receipt and processing of incoming data and provide it to customers via the World-Wide-Web. The USGODAE server will also archive all incoming data. The program strategy selected for the design, development and deployment of the USGODAE server system will emphasize a scalable, redundant high availability, high reliability architecture. This strategy enables the server to have both preliminary capabilities and allows for the addition of functionality and changes as requirements are further defined.

2. NAVAL OCEANOGRAPHIC GLOBAL ATMOSPHERIC PREDICTION SYSTEM

Naval Oceanographic Global Atmospheric Prediction System (NOGAPS) version 4.0 runs on a Cray supercomputer, and is a 160 spectral wave forecast model with 24 modified sigma corrected pressure levels from the surface to ten millibars. These sigma levels are concentrated near the upper levels and surface, the areas that most influence the weather. The internal resolution of the model is 0.75 degrees with an output of every one-degree. The model consists of four major components: data quality control, data analysis via multi-variate optimum interpolation (MVOI) model initialization (normal mode initialization), and the spectral wave forecast model. Output includes: absolute vorticity, air temperature, convective clouds, convective precipitation, divergence, dew point depression, geopotential heights, ground wetness, Sea Surface Temperature (SST), ice coverage, lifting condensation level, Infrared (IR) radiative flux, latent/sensible/total heat fluxes, snow depth, wind direction/speed, surface pressure, solar radiation, cloud cover, total precipitation, velocity potential, vapor pressure, and wind stress assimilation.

III.   THE ARGO PROJECT

The Array for Real-time Geostrophic Oceanography (ARGO) is a broad-scale global arrangement of autonomous floats that collect in situ ocean T and S profile data.

A.   ARGO DEVELOPMENT

The National Science Foundation (NSF) and the Office of Naval Research (ONR) sponsor ARGO. ARGO is a pilot project of the GOOS and is also supported by CLIVAR and WCRP. The United States has combined the scientific and operational objectives of ARGO with its worldwide span and interdisciplinary potential under the National Oceanographic Partnership Program (NOPP). A United States Float Consortium was formed to join academic and government scientists who have expertise in float technology, as well as float manufacturers. NOPP hopes to facilitate the planning and implementation of the U.S. ARGO project by combining the varied, though complimentary interests of federal agencies. The U.S. Float Consortium will join the collaborative efforts of four different academic institutions, including Woods Hole Oceanographic Institution and Scripps Institute of Oceanography, two governmental laboratories and two private companies, one of which is Webb Research Corporation in Falmouth, Massachusetts (Wilson, 2000). Duplicate efforts will eliminate previous breaks in multi-agency efforts. NOPP will ensure that the U.S. Float Consortium will be a single project that has a broad base of interest and support (Roemmich, 2000). ARGO is planned to be a major component of the world's ocean observing system. The concept of ARGO builds on existing upper-ocean thermal networks, extending their spatial and temporal coverage, depth range and accuracy, and enhancing them through addition of salinity and velocity measurements.

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1. Jason and ARGO

The name ARGO was chosen because of the project's close connection to the Jason-1 satellite altimetry mission. Jason-1 is a collaboration of the National Aeronautics and Space Administration, NASA, and the Centre National d'Etudes Spatiales, CNES, the French Space Agency. Jason-1 collects global sea level measurements, sea surface temperature and the speed and direction of wind at the ocean surface. Jason-1 continues the efforts of the NASA/CNES TOPEX/Poseidon satellite in 1992. Jason-1 also utilizes other satellites operated by NASA, NOAA, and the Japanese Space Agency (Wilson, 2000). In Greek mythology, Jason required his ship, the Argo, for his epic ocean voyages. Unfortunately, satellites cannot collect measurements from beneath the surface of the ocean. The present day Jason also requires an ARGO to accomplish its mission (Roemmich, 2000). Together, the modern Jason and ARGO can provide regular global sea surface heights with subsurface measurements and critical data for ocean circulation prediction. The combination of satellite altimetry measurements and globally spaced profiling floats will provide a dynamically complete description of the height of the sea surface and the subsurface mechanisms below the ocean's surface. The Jason and ARGO projects will complement one another and investigate a broad range of space and time scales. The data collected from numerous global profiling floats coupled with satellite altimetry will provide more accurate ocean state estimation than either system could provide on its own (Roemmich, 2000).

2. The Scope of ARGO

The global scope of ARGO requires international participation. The Climate Variability and Predictability Project (CLIVAR) and GODAE formed an International ARGO Science Team to coordinate the design and implementation of ARGO. The inherent international nature of

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ARGO has been unique in building a global consensus that includes scientists and operational and agency participants. All ARGO participants have agreed to the need for global coverage. In order to achieve this, they have agreed to deploy some floats outside of their particular region of interest. The achievement of global coverage will raise the level of national programs until the goal of deploying 750 floats per year by 2002 is attained. Until 2002, there will be a skeleton array in place to initiate GODAE in 2003 and complete the array of 3,000 floats by 2005 (Roemmich, 2000).

B. IMPLEMENTING ARGO

1. ARGO Floats

ARGO will be comprised of about 3000 autonomous instruments deployed in floats and distributed throughout the world's oceans at three-degree spacing in latitude and longitude. The floats will dive to and "park" at an electronically set depth utilizing a pressure sensor. The "parking," or reference of each float will vary, the average parking depth will be ~1000m. Some floats will park as deep as 2000m, while others will only reach a depth of 50m. The floats are programmed to return to the sea surface approximately every ten days. Again, float surface intervals will vary. A diagram of the float cycle is shown in Figure 1. As the float surfaces, it will take T and S profile readings. Each float will provide approximately 100 temperature/salinity profiles and reference velocity measurements per year. The instruments onboard each float have an approximate four to five year lifetime on a ten-day reporting cycle. As float positions are known, the floats can be retrieved. In the case of instrument failure, equipment can be replaced. Onboard batteries can be recharged, and instrument upgrades can be made, effectively recycling and modernizing the float for another lifetime (Wilson, 2000). Figure 2 is a diagram of the ARGO float and its instruments.

Once at the surface, the float will relay data collected via satellite. ARGO aims to transmit this data in less than 12 hours to forecast centers for operational use. This rapid transmission will be able to provide the observed physical state of the global ocean at any given time. The data will be scientifically quality controlled and accessible via the World-Wide-Web. The web server for data collected by floats purchased by the United States, termed "USGODAE," will be hosted at Fleet Numerical.

Computerized simulations of the float paths indicate that they will not cluster together when parked at depth. Rather, the floats will follow the deep ocean circulation and maintain a separation of a few hundred kilometers (Wilson, 2000). A projected depiction of the locations of these 3,000 floats is available in Figure 3.

Oceanographic and other research vessels will deploy ARGO floats. Commercial vessels can also deploy floats as they traverse international shipping routes. The floats can be released either over the side of a ship directly or packaged in a biodegradable box (Figures 4a and 4b). The ARGO floats can even be fitted with parachutes and deployed by plane to remote areas of the ocean (Wilson, 2000). (Figure 5).

2. ARGO Measurements

The upper layers of the oceans can store more than a thousand times the heat than the atmosphere does. Changes in currents, salinity, temperature and the transfer of heat beneath the surface will affect conditions at the surface. Therefore, subsurface measurements are essential to air-ocean interface exchanges.

$$h' = \frac{1}{8} \int_{\mathrm{Pr}_{ef}}^{0} (\rho')^{-1} dp + \frac{1}{\rho g} p'(z_{ref}) \qquad (1)$$

Equation (1) describes fluctuations in sea surface height. The left-hand side of the equation, h, is sea surface height. On the right-hand side of the equation, ρ is the density of water, a function of pressure, temperature and salinity. p is pressure, and g is the acceleration due to gravity. Primes indicate mean time anomalies. On the left-hand side, a satellite altimeter can be used to measure the sea surface height. The first term on the right-hand side can be calculated directly by the measurements of pressure, temperature and salinity reported by the ARGO floats. The density, or dynamic height, measures the expansion or contraction of the water column due to changes in the properties of the water, such as thermal expansion. The second term on the right-hand side represents the float's velocity from the time that it drifts at the reference depth between profiles (Roemmich, 2000).

$$\nabla p = \rho f u \qquad (2)$$

Equation (2) describes large-scale drift in geostrophic balance: f is the Coriolis parameter and u is the drift velocity. The drift can be used to calculate horizontal pressure gradients at the reference depth, or the reference pressure, P_{ref}. In equation (1), this pressure term measures the changes in mass of water above the reference depth. This includes pressure changes due to wind-driven ocean circulation. Therefore, the density and mass-related contributions combine to total large-scale sea level variability, as measured by the satellite altimeters and the ARGO floats (Roemmich, 2000).

Current XBT data has spacing within a few hundred kilometers. This allows for the determination of heat storage in the surface layer on a seasonal time-scale. ARGO floats can

provide the same data with a greater number of data collection points, allowing for the observation of interannual fluctuations. The examination of heat storage measurements will provide much needed constraints on air-sea heat exchange in coupled oceanic and atmospheric models (Roemmich, 2000).

On a global basis, spectral analysis of altimetric data shows that half of the variance in sea level is at wavelengths shorter than 1000 km. Climate prediction requires wavelengths longer than 1000 km. The ARGO float array with three-degree spacing will include these longer wavelengths (Roemmich, 2000).

3.   GODAE and ARGO

The ARGO project is crucial to the success of GODAE. The data ARGO collects will be utilized by GODAE in order to predict the "weather of the ocean." GODAE requires subsurface ocean data in order to ease the constraints of surface forcing and surface height and to improve upon testing and comparison in assimilation models. GODAE utilizes a strategy of cooperation between the role of direct and remote observing networks and the role of models and data assimilation in integrating incoming information and producing useful and practical outputs (AST, 1998).

4.   ARGO, GODAE and WOCE

The World Ocean Circulation Experiment (WOCE) provided global data, but took seven years and several ships to do so. ARGO will be able to provide near-real-time global, subsurface coverage of T and S to an average depth of 1000m. ARGO will improve our basic understanding and knowledge of the sea, including water column structure, circulation and mass, heat and salt budgets. The data collected will make global climatologies of subsurface temperature and

salinity available, including identified statistical errors. ARGO will also provide time-series of heat and freshwater storage and the structure and volume of the global thermocline and intermediate water masses. The global depiction of the mean and variability of large-scale ocean circulation, interior ocean masses and heat and freshwater transport will be completed by the ARGO project (Roemmich, 2000). This large-scale picture will allow oceanographers to view the dominant patterns of variability in the sea, such as ENSO, the Pacific Decadal Oscillation, North Atlantic Oscillation, Antarctic Oscillation, the Indian Ocean Dipole and the Antarctic Circumpolar Wave. These major circulation occurrences are potentially predictable.

Data collected during WOCE shows that ocean currents transport huge quantities of excess heat from the tropics to mid-latitudes alone. This is comparable in magnitude to the heat transported throughout the atmosphere. WOCE also revealed a large interannual variability in the ocean heat transport. More than 300 floats were deployed during WOCE to the South Pacific. This number of floats provided mean mid-depth variability throughout the duration of the experiment, but time variability could not be measured. ARGO increases the number of floats to 3,000, and the area covered to the entire globe. These increases enable ARGO to create accurate depictions of seasonal and interannual variability in temperature, salinity and circulation. As the number of floats in the North Atlantic has increased, the need for a dense array has become more apparent. An increased number of data collection points will allow large-scale change to be observed over the noise of mesoscale eddy fields. WOCE discovered mid-depth ocean warming on decadal time-scales in the North Atlantic. This basin-scale signal can be verified with the dense ARGO array.

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IV. DATA

A. USGODAE DATA

The USGODAE server at Fleet Numerical currently hosts eight different data sets for GODAE. Most of these data sets are updated twice daily, at approximately 0000 and 1200 GMT. All data is available in Institute of Electrical and Electronics Engineers (IEEE) format via Hyper Text Transfer Protocol (HTTP) and File Transfer Protocol (FTP).

1. Oceanographic Data Available

- Altimetry: Ocean Topography Experiment (TOPEX) and European Remote Sensing Satellite (ERS) altimeter, Sea Surface Height Anomaly (SSHA), data;

- Multi-Channel Sea Surface Temperature (MCSST): Advanced Very High Level Resolution Radiometer (AVHRR), SST retrieval data;

- Surface Observations (SFCOBS): Ship *in situ* sea surface temperature measurements;

- Special Sensor Microwave/Imagery (SSM/I): Defense Meteorological Satellite Program (DMSP), sea ice concentration retrievals;

- Profile: Both fixed and drifting buoy data and bathythermograph data. Archived to December 1, 1998;

- Naval Oceanographic Office (NAVO): SST from NAVO model output.

Products and data can either be local to the data server or accessed via links to remote data sets populated and maintained by other groups.

2. Meteorological Data Available

Some Fleet Numerical meteorology data is also available on the site in an unprocessed format. Meteorological data available includes:

- **Aircraft Reports**: Aeronautical Radio Incorporated (ARINC) Communications Addressing and Reporting System (ACARS) and Upper Air Reports (AIRREPS);

- **Upper Air Observations**: Piloted Balloons data (PIBALS) and Rawinsonde data (RAOB);

- **Land Observations**: Both land observations and METAR data;

- **Surface Observations**: Both surface ship and buoy observations;

- **Satellite Observations**: Satellite Derived Observation Reports (SATOBS), Satellite Feature Tracked Wind Reports (SAFTW), scatterometer reports, SSM/I, Special Sensor Microwave/Temperature (SSM/T), Special Sensor Microwave/Temperature, Humidity (SSM/T2), and Television Infrared Observational Satellite (TIROS) Operational Vertical Sounding (TOVS).

Additionally, model output from either the Fleet Numerical global model NOGAPS, or the regional model, Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) is available from the server. NOGAPS forcing fields include winds, temperatures, and fluxes. Data has been archived to October 1, 2000. The file consists of individual grib files for each parameter, level and forecast increment. The NOGAPS model predicts out to 144 hours.

B.   METHODOLOGY

1.   Data Selection

There are vast quantities of data available, covering several different areas in both oceanographic and meteorological studies. Specific data types were selected for use in this thesis using the following criteria:

Does the data type relate directly to ocean conditions and oceanographic research? This narrowed the types of data down considerably. All meteorological data, both observational and assimilated, was eliminated in order to focus solely on oceanographic parameters. This focus follows the objective of GODAE and allows this analysis to measure the utility of GODAE as an oceanographic data source.

Is the type of data one that is vital to the success of the GODAE project? This criterion served as a method of eliminating the possibility of choosing a data type that may not yet be fully implemented into the GODAE plan and is therefore irrelevant to this study. The emphasis of this thesis is to evaluate data that is available now, to forecast the utility of this data and the additional data that will be available in the future, and to promote continuation of this type of analysis for the GODAE data.

Is the data in a format that can be readily processed? This ensured that selection of a data type would not end in an unsuccessful attempt to process, view and assess the data for utility and feasibility. Although all data types available are functional in some aspect, processing and formatting issues for this analysis were addressed to ensure successful data retrieval.

Is the data of a magnitude that can be processed with the available resources? The choice of data depended on the availability of disk space for retrieval and processing. Although several

data sources met this standard, some were much too large to ingest and process into the visualization software used without significant processing time and resources.

Will the data play a significant role in future oceanographic research? The final criterion involves some subjective estimation. Although it is likely that all of the data types available will be important in understanding the ocean, its condition and processes, care was taken to choose a data type that will likely be relevant for years to come.

This thesis utilized data collected by drifting buoys, specifically by the ARGO floats. Drifting buoy data met all of the criteria for this report. ARGO float data was of particular interest due to the interdependence of GODAE and ARGO. Both projects are still in their beginning stages, and will not reach their full potential for a few years. This thesis is meant to determine the feasibility of these two projects at present, and forecast their utility for oceanographers once the projects have reached their full potential.

2. Data Retrieval and Processing

The actual retrieval of ocean profile data from the USGODAE server reflects one of the guiding principles of the GODAE project: open and readily accessible oceanographic data by any potential user. File size ranged from 200 to 300Kb per day of profile data. Data files are updated twice daily, so an expected time delay of approximately 12 hours exists for near-real-time data. Files on the server are stored in a compressed state and in IEEE format.

Buoy profiles available on the USGODAE server begin on 1 September 2000 and continue up to the present day. This thesis analyses data, from 1 September 2000 to 8 March 2001.

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Fleet Numerical intends to utilize the Ferret programming language in conjunction with Live Access Server (LAS) to provide customers with a graphic representation of GODAE data on the USGODAE data server. Ferret is an interactive visualization and analysis environment developed at NOAA's Pacific Marine Environmental Lab (PMEL) in Seattle, Washington. Ferret was chosen because of its past success in the visualization of meteorological and oceanographic products.

Although use of ferret as a visualization tool was initially attempted, the programming language required proved to be indecipherable. Differences in data formats, initial startup time in developing the code necessary and software support led to a reevaluation of the visualization method.

Matlab software is gainfully employed by both the Oceanography and Meteorology Departments at the U.S. Naval Postgraduate School in Monterey, California. Matlab version 6.0 was the successful second choice for visualization in this analysis due to familiarity with the language, significant local software support and straightforward data format conversion methods.

Data was converted from IEEE into American Standard Code for Information Interchange (ASCII)-text format through a FORTRAN 77 script available on the USGODAE server. This script creates an executable file that searches a table of ocean observation types available and compiles a listing of available ocean observation data types for use in ASCII format. The Matlab program can easily read ASCII formatted data.

C.   BUOY PROFILE DATA

1.   Data Format

The resultant ASCII file is a text record of all ocean profiles collected and archived on the USGODAE server for the chosen day. Header information was stripped out of the individual profiles, put into column format, and concatenated onto the rest of the profile data that was already in column format. This column-type, or array format allows the data to be easily read and processed by Matlab.

There are 41 different profile data types available on the USGODAE server. These are listed in Table 1. Buoy profile data is filed and stored on the USGODAE server by year and day. Each file then contains the profiles collected for that particular day. The header data in each file includes the Date Time Group (DTG) of the file, the data directory path, the number of profiles it contains and the maximum number of levels reported. The profile data follows, and is separated by dashed lines. Each profile is in approximately the same format and includes the buoy identification number, or profile "call sign," the profile latitude and longitude, the DTG that the profile was observed, as well as the DTG that the data was received, recorded bottom depth, the profile data type, i.e. "Drifting Buoy," the total number of levels recorded, the number of observed T and S levels, the T and S gross error, the sea surface height anomaly, the sea surface temperature (SST) and the classification of the data.

There are three level counters within the profile data output. The total number of levels in the profile is indicated in line six, while line seven provides the number of observed temperature and salinity levels. Profile data is extended to the bottom depth using Modular Ocean Data Assimilation System (MODAS) data. MODAS temperature and salinity values are inserted into the profile when measured values are not available.

Observed buoy profile data follows the above individual profile header information and is in a nine-column format. These columns are titled and include depth, temp_std: temperature standard deviation, sal_std: salinity standard deviation, temp_prob: temperature probability, sal_prob: salinity probability, temperature climatology, MODAS, glbl and regn. The standard deviations are static estimates of variability computed from historical data. They are derived from the data used to build the MODAS climatology fields and are distributed as part of the MODAS database. These statistics are not updated dynamically on the USGODAE server. The climatology data available is imported from the U.S. Navy-standard Generalized Digital Environmental Model (GDEM) climatology. The columns labeled glbl and regn, are placeholders for future global and regional data. A sample profile is shown in Figure 6.

In order to speed up processing time and achieve the desired output, the ASCII file was rearranged even further. Observations from the single file format were divided out and placed into an individual file by date, allowing the data to be easily searchable. The new file name format contained the identification number of the instrument platform and the DTG of the observation. This allows searches to be performed over specified time periods and for specific instrument platforms. Latitude and longitude were not incorporated into the file name as the observations were going to be presented on a world map.

The file created for each observation followed a precise format to aid in data accessibility by Matlab. Each observation was searched for the desired instrument platform type and the associated information was written to a file with that instrument platform's identification number and the observation DTG. The new file contained the profile data recorded for depth, T, S, GDEM climatological temperature, latitude and longitude. MODAS data was included in the T and S reports.

2. Data Visualization

A supplemental file to assist in visualization was created to list each observation in the data set by instrument platform identification number, location (latitude and longitude), temperature recorded at the surface and the DTG. The desired visualization output required the end user to have the ability to search for specific subsets of data, visually separate specific groups of observations and view graphical representations of T versus depth, S versus depth, T versus GDEM climatology T and, T versus S (T-S) diagrams.

The world map used as the initial figure of reference is available in Figure 7. The user can visualize data over the entire world, or zoom in using the appropriate function button on the toolbar, as seen in Figure 7.

The ability to search for specific subsets of observations was greatly aided by the use of the identification number/observation DTG file naming convention. This format allowed the Matlab program to search the supplemental file for a particular identification number using the toolbar seen in Figure 8 and display all locations reported by a particular buoy. The toolbar in Figure 8 also allows the user to search for buoy locations during a specific month or day. These subsets of data can be selected in combination and can also be differentiated by color using the toolbar in Figure 9. The figure can be reset to remove all previously shown data.

Graphical representations of profile data available for specific observations can be generated using the previously selected data sets as a guide. Selecting the type of profile desired from the toolbar seen in Figure 10 initiates a function that will follow the user's cursor across the displayed map area, highlighting the nearest observation to the cursor location on the map, Figure 11a, and showing a new window with information for that observation, Figure 11b. This information will assist the user in identifying the desired observation correctly to produce the

corresponding profile. The data for each observation provided is the identification number, DTG of the observation, latitude, longitude and SST. Using this information, the user can narrow down even a large group of observations to a single data point for analysis. When the user selects the data point, a new window appears. This window contains axis labels, the buoy identification number and the observation DTG.

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V.   GODAE DATA IN THE NORTH ATLANTIC

The North Atlantic Ocean is bordered by several oceanographic research facilities both in the U.S. and Europe. It is the most widely researched area of the ocean. As GODAE and ARGO are not yet full-strength, the majority of profiling floats are currently in the North Atlantic Ocean. Figure 12 shows all GODAE buoy locations differentiated by month from September 1, 1999 to March 8, 2001.

Circulation in the North Atlantic can be characterized by the northern subtropical gyre, Figure 13, which consists of the North Atlantic Equatorial Current, the Gulf Stream, the North Atlantic Drift and the Canary Currents. The Atlantic Equatorial Countercurrent, the Labrador Current, the East Greenland Current and the Guinea Currents also influence circulation in this basin.

GODAE data can be used to visualize major oceanographic features such as currents and large-scale eddies. The study of the following North Atlantic features will be significantly improved once GODAE and ARGO are fully operational.

A.   THE WESTERN BOUNDARY

1.   The Gulf Stream

The Gulf Stream is a typical western boundary current. Its flow can be described as the Florida Current, the Gulf Stream proper the Gulf Stream Extension, and some continuation into the North Atlantic and Azores Currents.

2.   Gulf Stream Rings

As the Gulf Stream turns away from the coastline, eddies form on either side of the flow. On the northward side of the Gulf Stream, anticyclonic warm-core eddies are formed. To the

south, cyclonic cold-core eddies form. Gulf Stream eddies are also referred to as Gulf Stream rings. Rings formed to the north of the Gulf Stream deteriorate quickly and are then reincorporated into the main flow. Southern rings maintain their integrity for a number of days, propagating toward the southwest where they then deteriorate and are also reincorporated into the main flow.

B.   THE EASTERN BOUNDARY

1.   The Canary Current

The Canary, or Iberian Current dominates the eastern boundary flow in the North Atlantic. This current flows from the northern tip of the Iberian Peninsula, through the Canary Islands to the northwest coast of Africa. Two major topographic features distinguish this from other eastern boundary currents: the Canaries Archipelago and the Strait of Gibraltar.

The islands influence the current, intensifying it as it passes between the islands and produces a "shade" zone, with warmer water south of the islands, creating an accumulation of marine biomass. Contact between the current and the shade zones results in two eddies, a cyclonic gyre in the west and an anticyclonic gyre in the east, acting to accumulate zooplankton from the north. Cyclonic cold-core eddies enhance primary production by upwelling nutrient-rich thermocline water into their centers. Eddies closer to the shore may interact with the filaments of cool upwelled water and could contribute to their production by entraining upwelled water around their perimeter. Upwelling filaments off of the Iberian Peninsula can be seen in Figure 14.

2. Coastal Upwelling

As eastern boundary currents flow southward in the northern hemisphere, the Coriolis force deflects flow to the west. This offshore flow is balanced by coastal upwelling. The width of this upwelling region is narrow, <100km, but exceeds the width of the shelf in most places. Increases in primary productivity in this region are due to upwelling, mixing and advection. Major upwelling occurs at the numerous capes in this region due to outward shifts in the current. Productivity is high around the upwelling centers at the capes. The continental shelf off of the African continent has been considered as an important area for primary production in this region of the world, and produces 5% of the world's fishing industry.

3. Meddies

The Portuguese continental slope is the source region for the spreading of the Mediterranean water tongue that spills through the Strait, introducing self-contained, slowly drifting, highly energetic intrathermocline vortices called "Meddies". Meddies rotate, preserving their original heat, salt content and potential vorticity over large distances as they travel westward.

C. GODAE DATA IN ACTION

The North Atlantic area of study was chosen to illustrate GODAE data in action because most of the ARGO floats that have been deployed at this time are located in the North Atlantic. Once all 3,000 ARGO floats have been released, data return will be from more evenly spaced locations. An evaluation of a region, such as the North Atlantic, also allows for the assessment of the relative success of the experiment to date. Visualizing GODAE data from a buoy in the

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North Atlantic, this thesis will identify the scope of possibilities for utilizing this data and examine its effectiveness in regional oceanographic studies.

Figure 12 is a Matlab display of all USGODAE drifting buoy available from 1 September 2000 to 8 March 2001. Data has been color coded by month, according to the legend. Figure 15 zooms in on the world map to isolate the North Atlantic.

In this display, buoy locations in the western Atlantic are mainly single points of data. Buoys here were either recently released or were programmed to report only once a month.

In the eastern Atlantic, some buoys are reporting every few days, as anticipated by the ARGO plan. Figure 16 is a closer look at the eastern Atlantic. This display shows a typical spaghetti diagram. Large-scale Lagrangian flow can be interpreted. Neither surface nor deep ocean currents can be determined directly as the buoy location depicted is the surface latitude and longitude when the float rises to transmit its report. Between locations on the map, the buoy has been drifting at its programmed depth.

At this point, the Matlab program allows the user to highlight individual map points, or buoy locations. Once highlighted, a second window will appear giving the buoy identification number, the DTG of the profile, latitude and longitude and the surface temperature. This allows the user to track the movement of a single buoy simply by moving the cursor over points on the map.

This process was used to highlight buoy 62570 in the eastern Atlantic, as seen in Figure 11a. Buoy 62570 was chosen because of its multiple reporting times and the apparent cyclonic flow of its reported locations. Matlab now allows the user to select the specific data point highlighted and choose from the four different profile reports available.

1. Temperature vs. Depth

Figure 17 is the temperature vs. depth profile for buoy 62570 on February 19, 2001 at the selected latitude and longitude. The thermocline is at a depth of approximately 160m. However, because MODAS T data is included in this profile report, close attention must be paid to the nature of the graph. The sample profile data report seen in Figure 6 is the profile data report for buoy 62570 on February 19, 2001. This data report reveals that for this particular transmission, the buoy only reported four levels. Therefore, the graph was created using only this data for actual observations, and the remaining data points were filled in with MODAS climatology. Perhaps this particular buoy was only programmed to report four data levels. Once GODAE and ARGO are fully operational, this T profile data will be very useful to oceanographers. It can be used to detect the depth of the thermocline. The SST data can be used to verify satellite measurements. Because some of the floats report more than one time in a single day, individual diurnal changes in an area can also be detected. Temperature changes at depth may also be useful in the detection and verification of eddies such as Gulf Stream rings or Meddies.

2. Temperature Observed vs. Temperature Climatology

Figure 18 is the observed temperature vs. the GDEM temperature climatology database for this buoy DTG and location. Again, there are only four observed levels. This particular profile report will be more useful for comparing data reported from many levels. It will be advantageous in the detection of large-scale changes in T in an event such as El Niño.

3. Salinity vs. Depth

Figure 19 is the salinity vs. depth profile for buoy 62570 on February 19, 2001 at the selected latitude and longitude. The halocline is at a depth of approximately 160m. However,

MODAS salinity values have also been inserted into this profile report. Like the T versus depth report profile, this S versus depth report profile will aid in the detection and verification of eddies. S values at the surface and at depth will also be useful in upwelling research.

4. Salinity vs. Temperature

Figure 20 is the T-S diagram for this buoy DTG and location. This diagram can be used to identify large-scale thermohaline circulation in a particular region using the data from several buoys in that region. Density differences can be visualized, and therefore water mass circulation can be tracked. Density at depth can also be useful in the study of ocean acoustics.

D. SUMMARY REMARKS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This analysis is meant to build the foundation for future use of the GODAE project at the Naval Postgraduate School. The GODAE and ARGO projects have been introduced, a few of their products have been examined and their potential has been outlined.

Future research in this area may include a reanalysis of GODAE once it is fully operational in 2003. It is recommended that analysis be done comparing GODAE data both with and without MODAS data. This would be valuable in determining the smoothing effect, whether positive or negative, of the incorporation of MODAS data. Satellite verification studies using GODAE SST, and potentially salinity are also highly recommended. Once more floats have been deployed, large-scale Lagrangian float tracking of currents and circulation can be completed. It would also be interesting to follow the reports of a single ARGO float, monitoring its path and observation changes, whether seasonal or diurnal, or both.

GODAE data, coupled with ARGO data, will be invaluable to oceanographers once both projects have reached their full potential. GODAE may prove to be the "one-stop-shopping" place for anyone requiring oceanographic data. With a complete GODAE database, an oceanographer may not even need to go to sea in order to obtain the measurements needed for research. The GODAE database will provide oceanographers with the tools necessary to predict the "weather of the ocean." Global climate prediction six to twelve months in advance will be feasible. As visualization on the USGODAE server becomes available, users will be able to create weather maps of ocean conditions. Though public interest in oceanography may never equal that of meteorology and an "Ocean Channel" may not be created, GODAE will undoubtedly influence wave and surf forecasts on the local news in coastal regions.

GODAE's climate prediction and emphasis on the air-sea interface will impact both meteorologists and oceanographers. Seasonal and climate forecasts will become feasible. The intensity of winters, the droughts of summers and the ferocity of hurricanes will be able to be predicted. The planning process for the use and conservation of economic resources such as water reserves, fuel supplies and grain will be improved. Shifts in oceanic conditions can dramatically affect fish populations, and in turn, affect the world's food source. GODAE will allow oceanographers to give advance notice of these types of ocean changes. Visualization of the ocean conditions in the North Atlantic will improve exponentially. The impact of ocean prediction capabilities in the oceanographic and meteorologic realms is tremendous. As ocean and climate prediction advance, the effect on the world's public will also be incredible. The development of the GODAE project, its relationship to the ARGO project, and Fleet Numerical's role in GODAE are exciting prospects to watch progress.
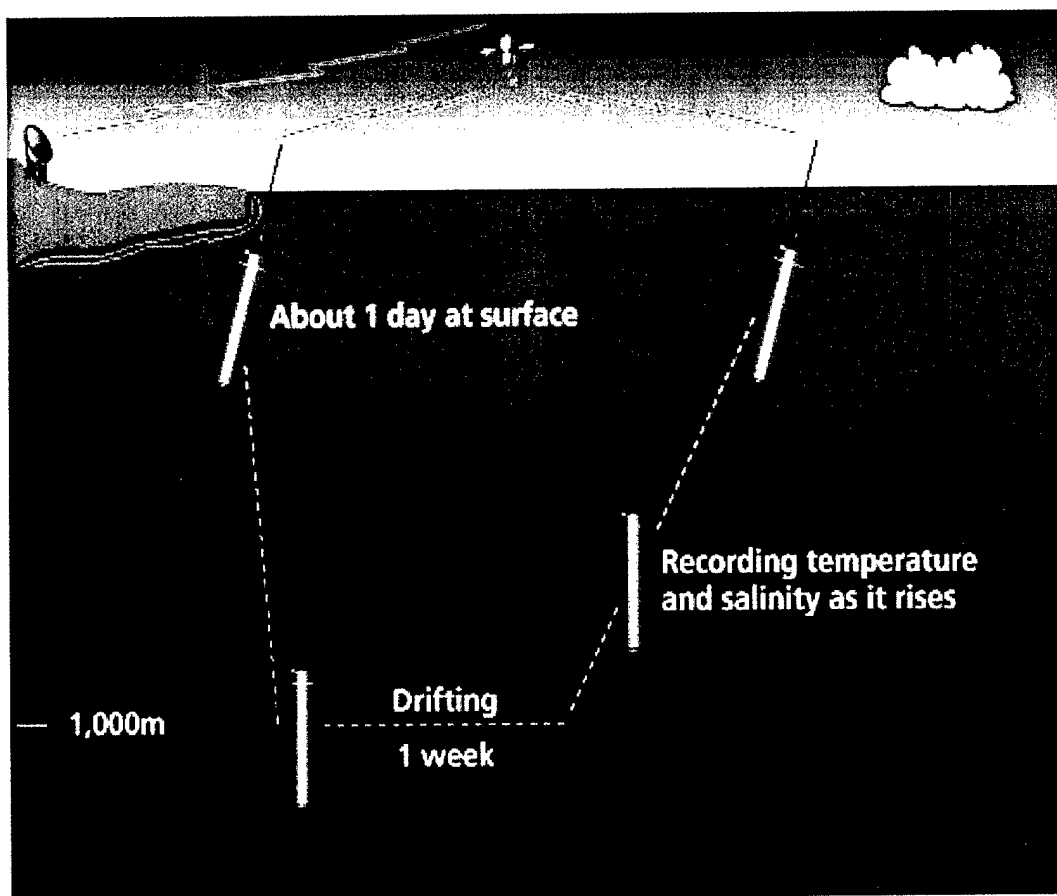
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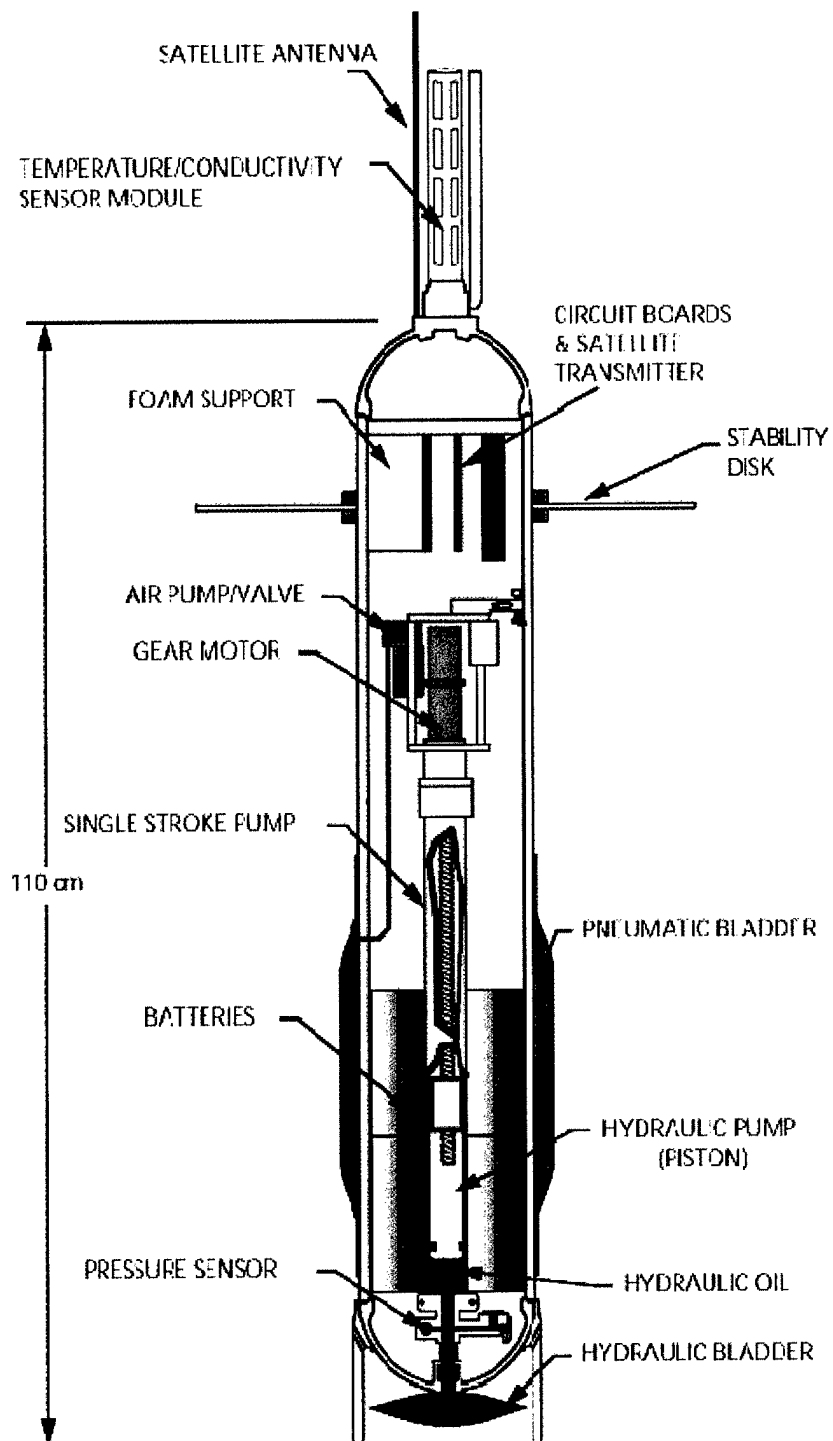Figure 1.   ARGO Float Data Transmission Cycle (Gwynne, 1999).

Figure 2.   ARGO Float Schematic (Gwynne, 1999).

Figure 3.   Projected ARGO Locations (AIC, 1999).

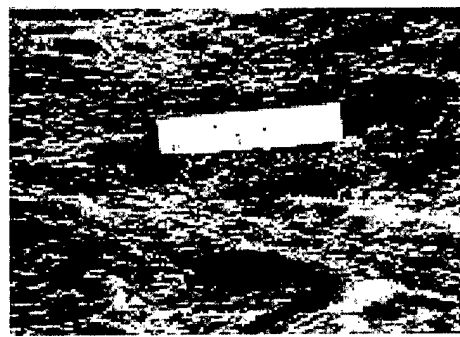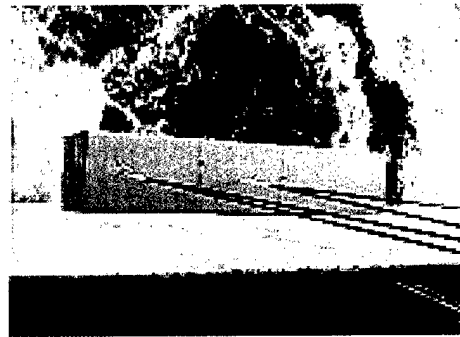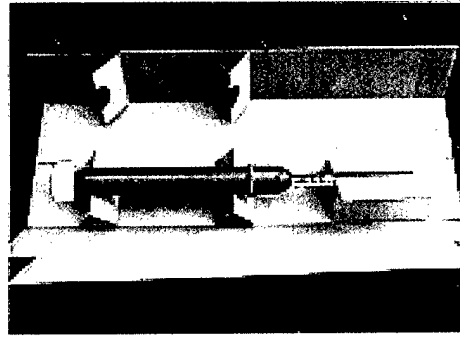Figure 4a. An ARGO float being deployed over the side of a ship (Gwynne, 1999).

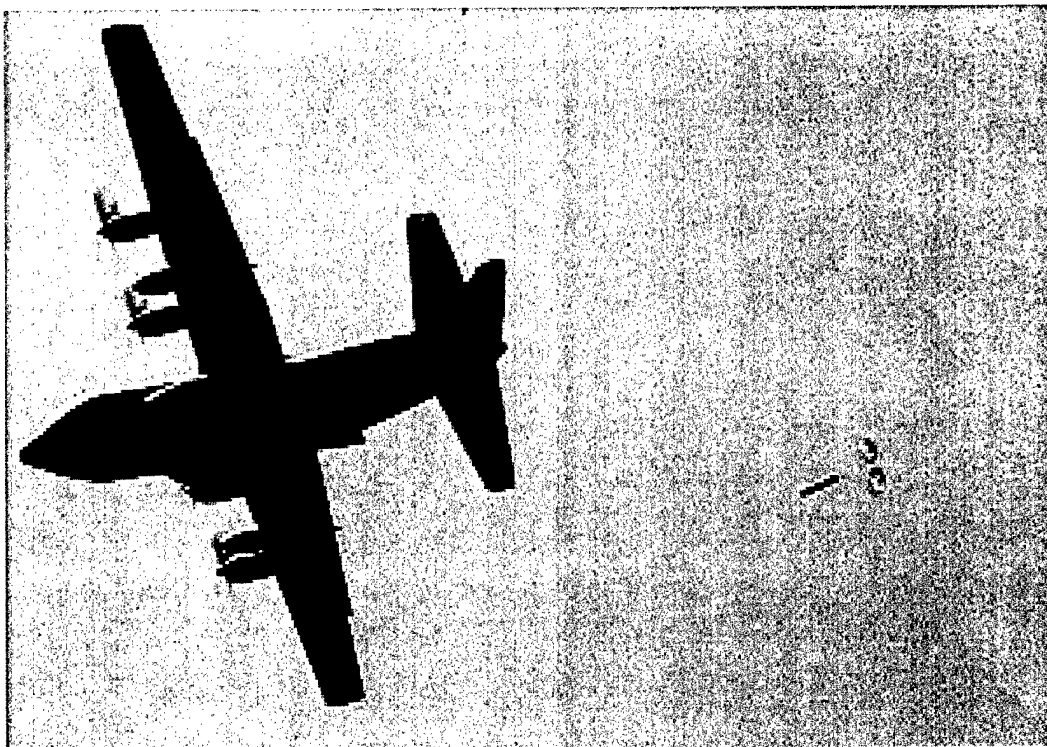Figure 4b. An ARGO float being deployed in a biodegradable box (Gwynne, 1999).

Figure 5.   An ARGO Float being deployed by airplane (Gwynne, 1999).

```
----------------------------------------------------------------------------
profile call sign       : "62570 "
profile latitude        :    44.95
profile longitude       :    -22.12
profile observed DTG    : "200102191500"
profile received DTG    : "200102192020"
DBDB5 bottom depth      :    -999.0
profile data type code  :       5
profile data type       : "   Drifting BUOY"
total number levels     :       4
observed temperature levels :      4
observed salinity levels   :      0
temperature gross error  :     0.6977
salinity gross error     :     0.5747
sea surface height anomaly :  -999.0000
sea surface temperature  :     13.61
security classification  :       "U"
```

depth	temp	salt	tmp_std	sal_std	tmp_prob	sal_prob	clim	modas	glbl	regn
0.0	13.61	35.76	0.63	0.09	0.6647	0.4966	13.00	13.61	-999.00	-999.00
20.0	13.55	35.76	0.62	0.09	0.6111	0.4763	13.02	13.60	-999.00	-999.00
40.0	13.53	35.77	0.61	0.09	0.5935	0.4725	13.02	13.59	-999.00	-999.00
180.0	13.50	35.80	0.55	0.09	0.8900	0.8011	12.62	13.17	-999.00	-999.00

```
----------------------------------------------------------------------------
```

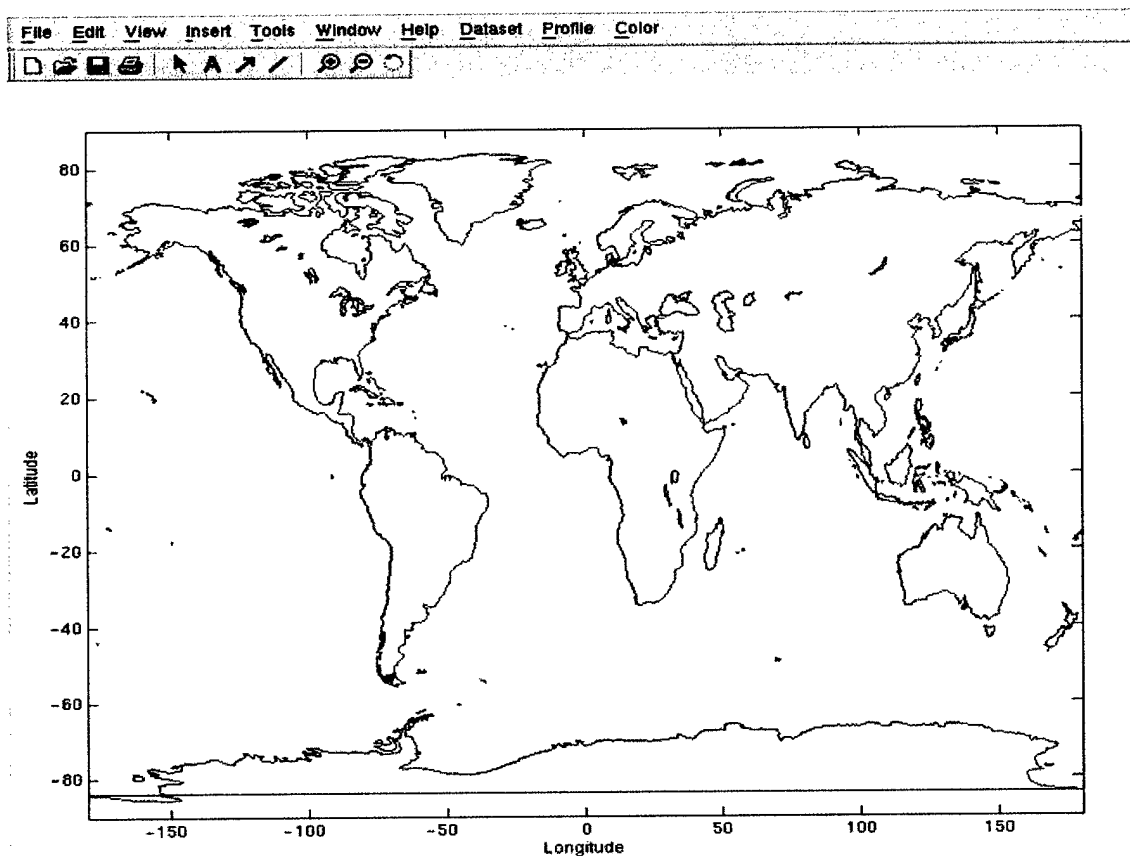Figure 6.   Sample Profile Report (USGODAE Data Server, 2001).

Figure 7.   Reference Map.
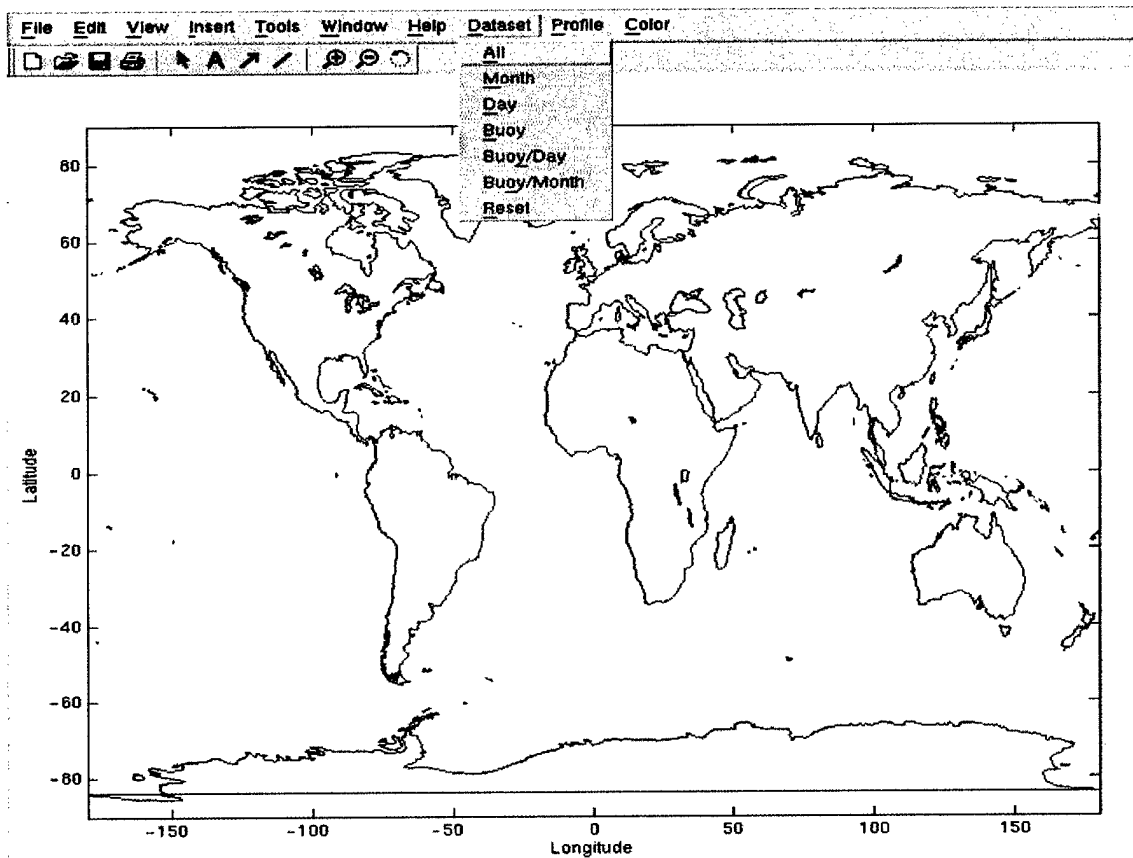
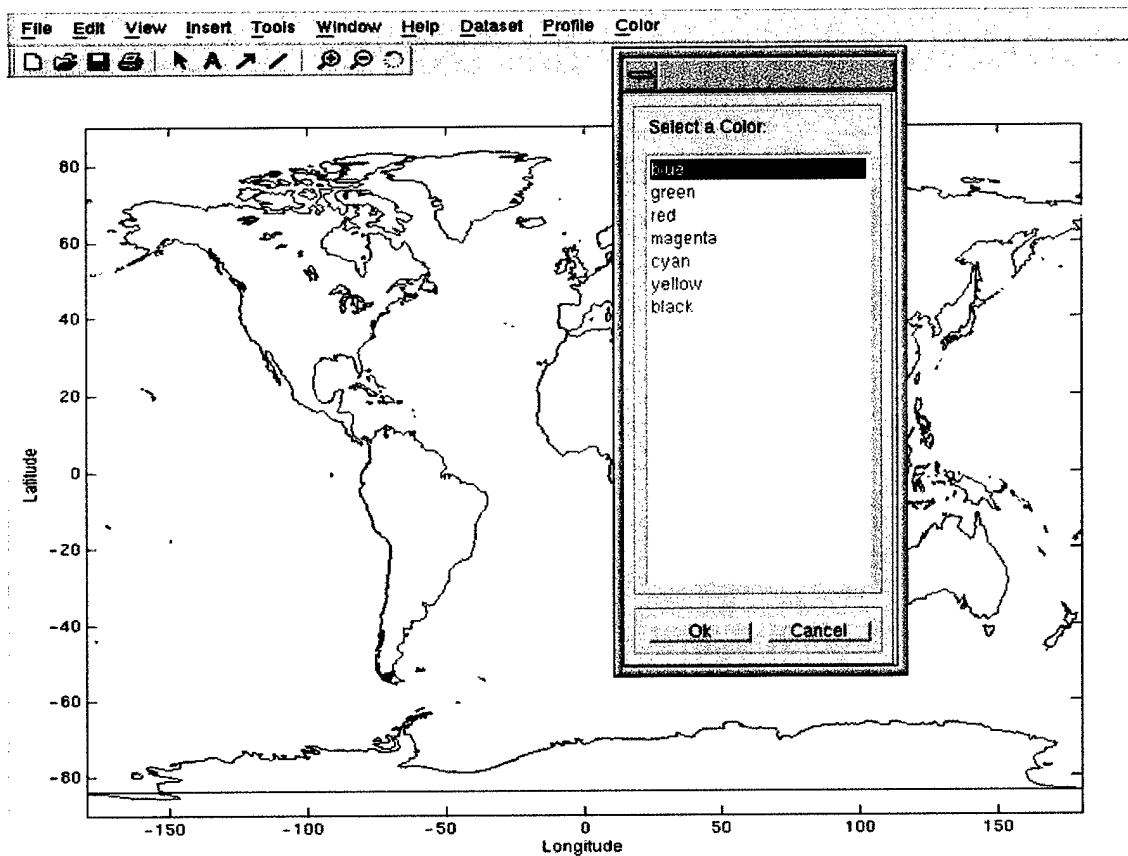Figure 8.   Dataset Menu.

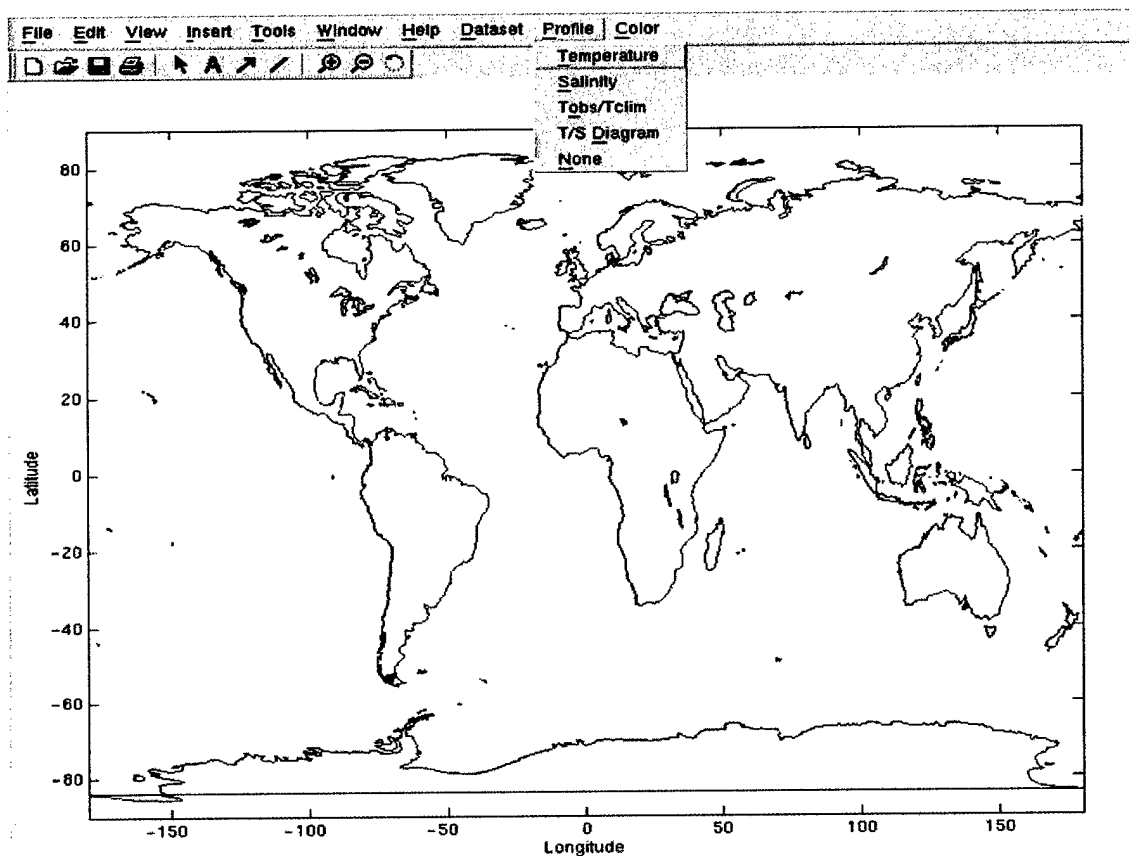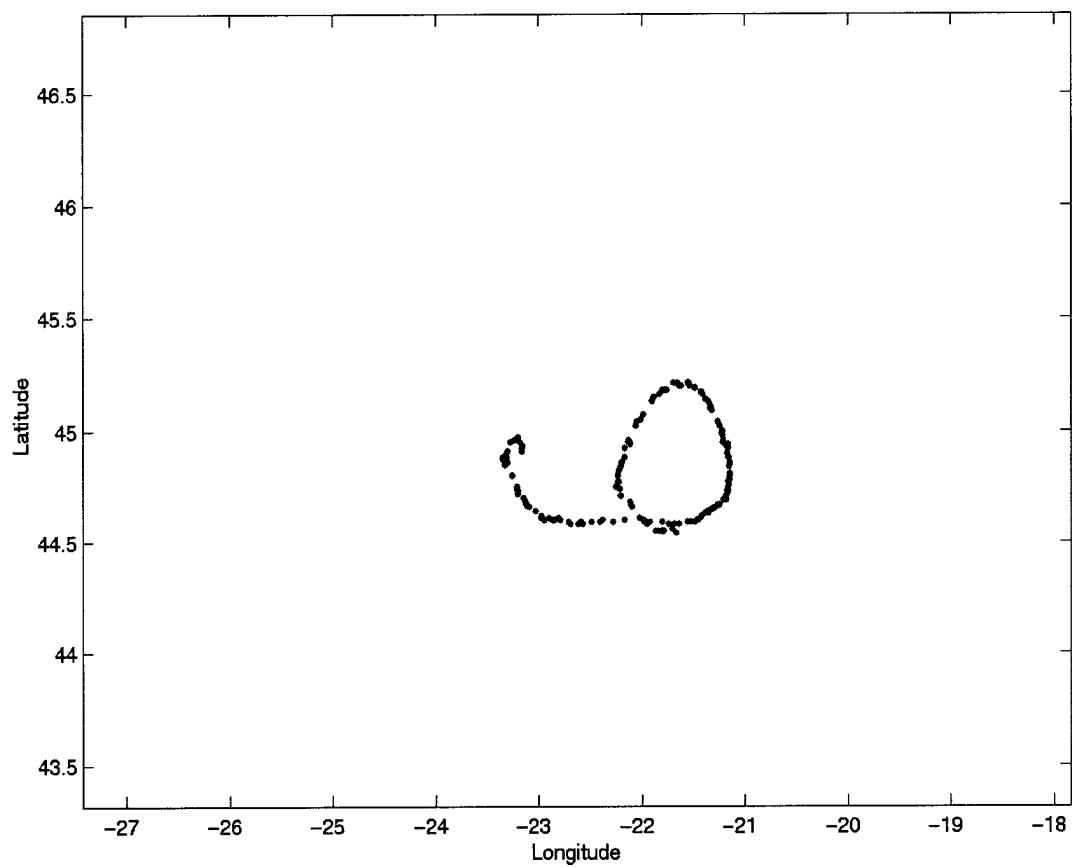Figure 9.   Color Menu.

Figure 10.   Profile Menu.

Buoy: 62570

Datetime: 200102192020

Latitude: 45.04

Longitude: -22.05

Surface Temp: 13.61

Figure 11a.   Highlighted Buoy (62570).

Figure 11b.   Highlighted Buoy (62670) Reference Data.
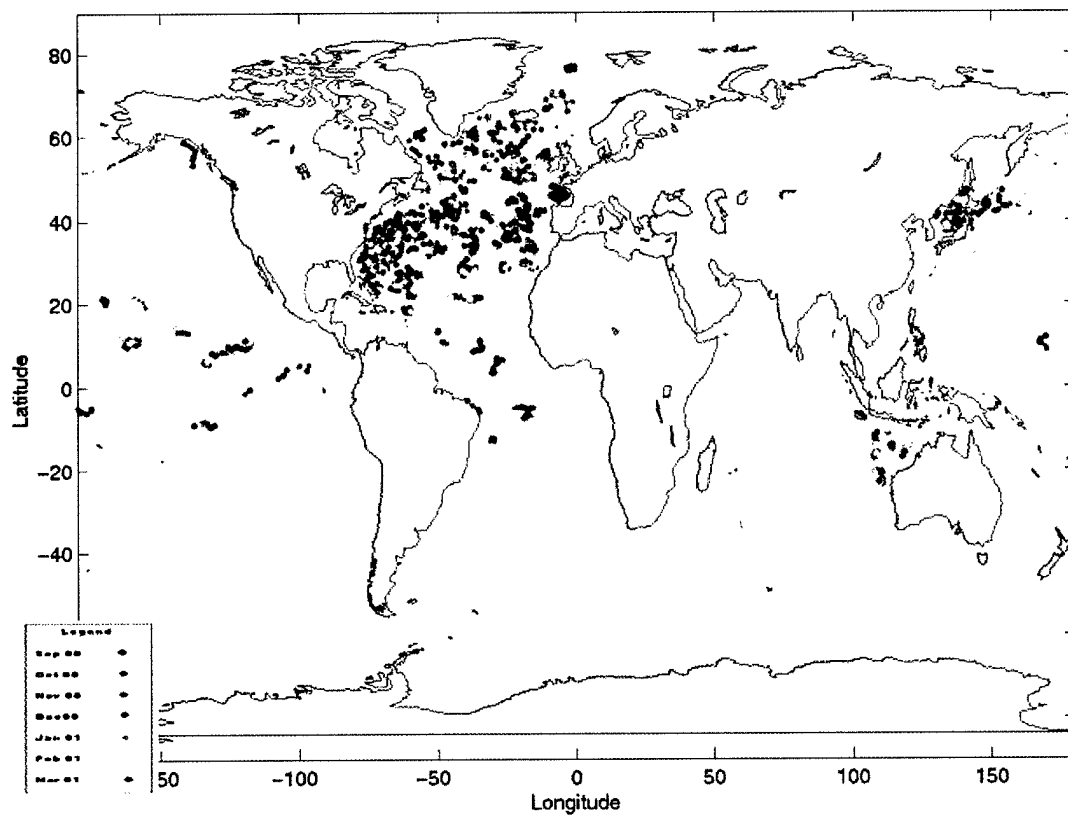
Figure 12.   GODAE Locations Around the World.

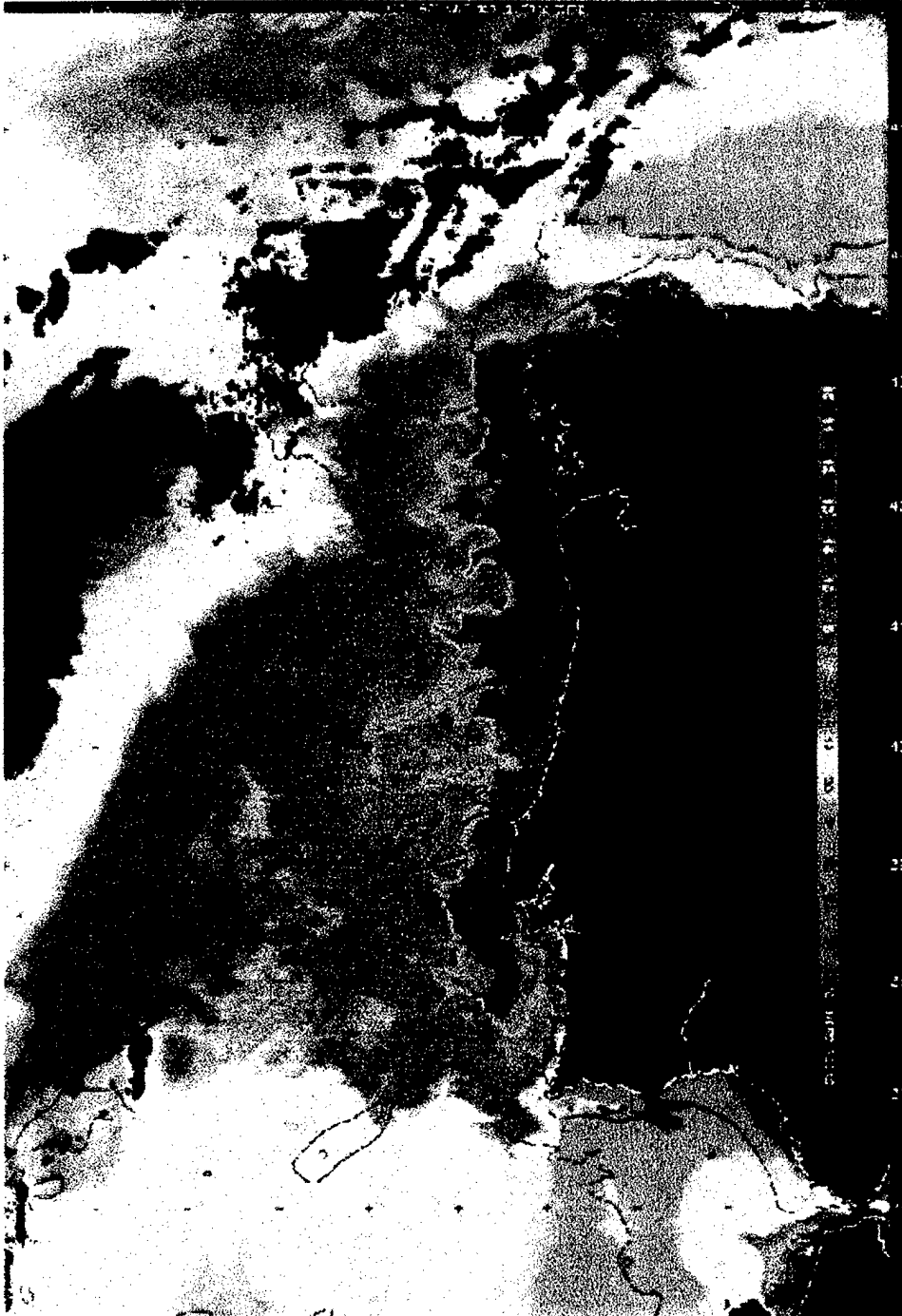Figure 13.   Northern Atlantic Ocean Currents (Rabenhorst, 1998).

Figure 14.   AVHRR SST from 27 July 1993 showing strong upwelling and numerous filaments off the west coast of the Iberian Peninsula (Remote Sensing Data Analysis Service (RSDAS), Plymouth Marine Laboratory, UK).
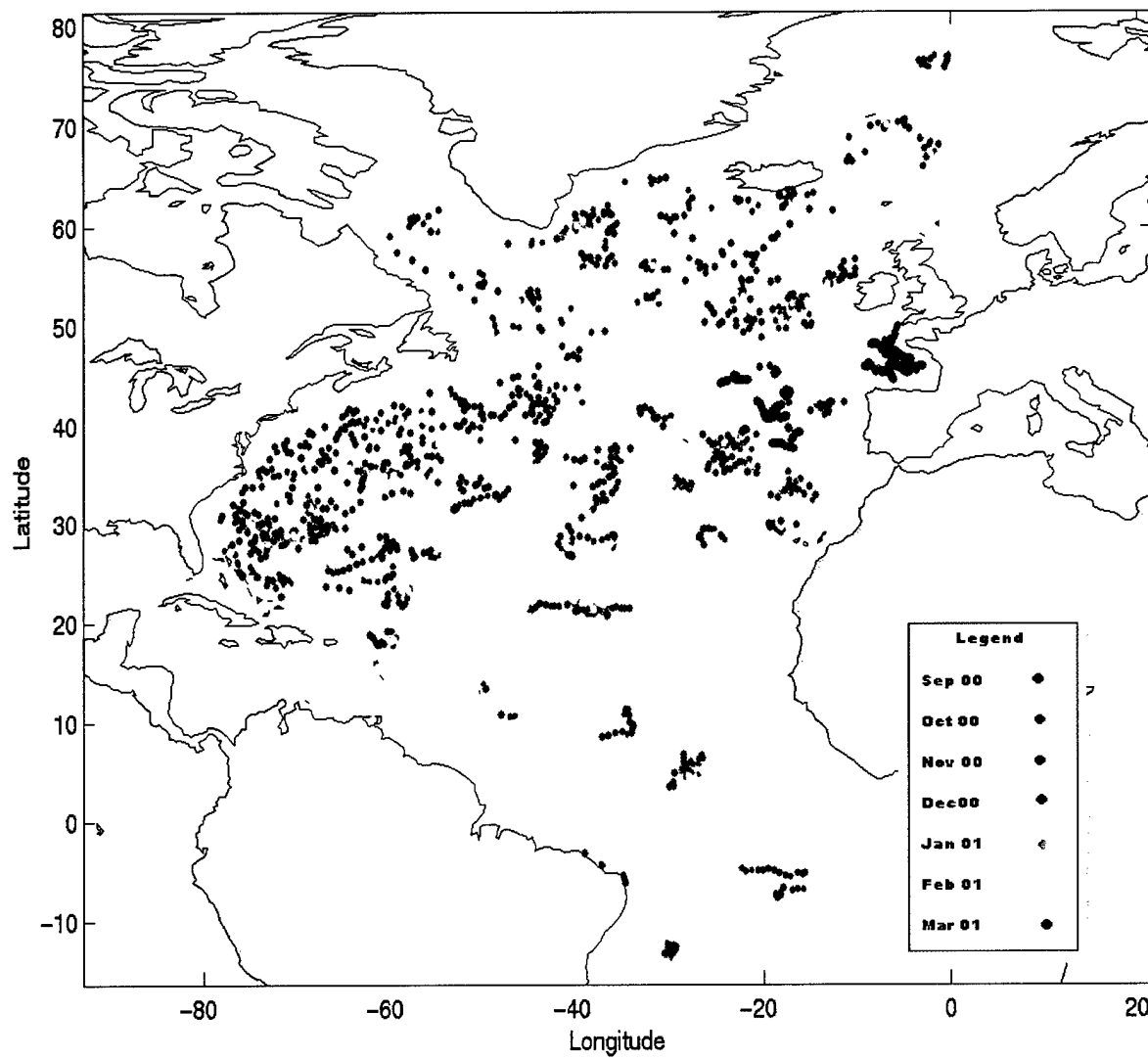
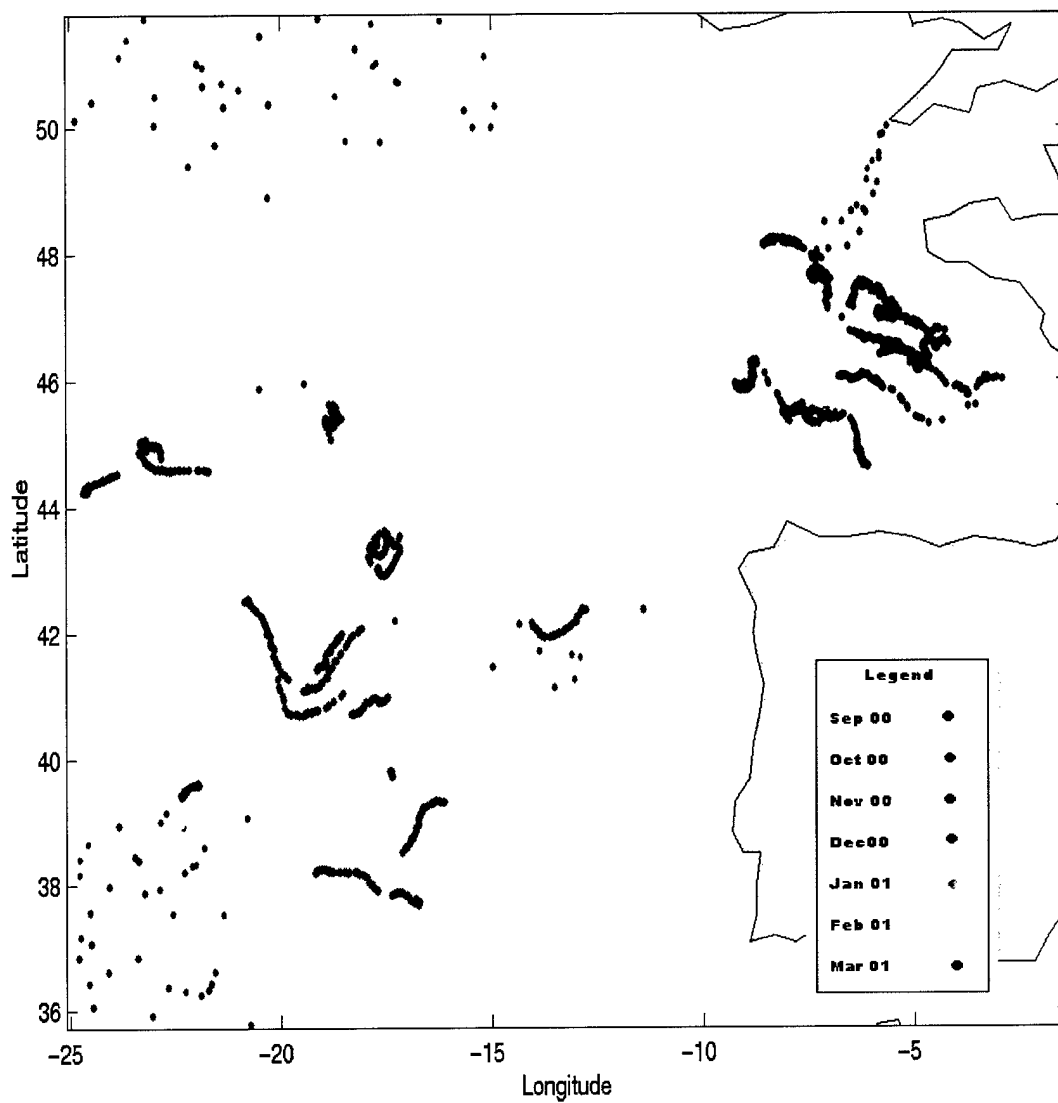Figure 15.   GODAE Floats in the North Atlantic.

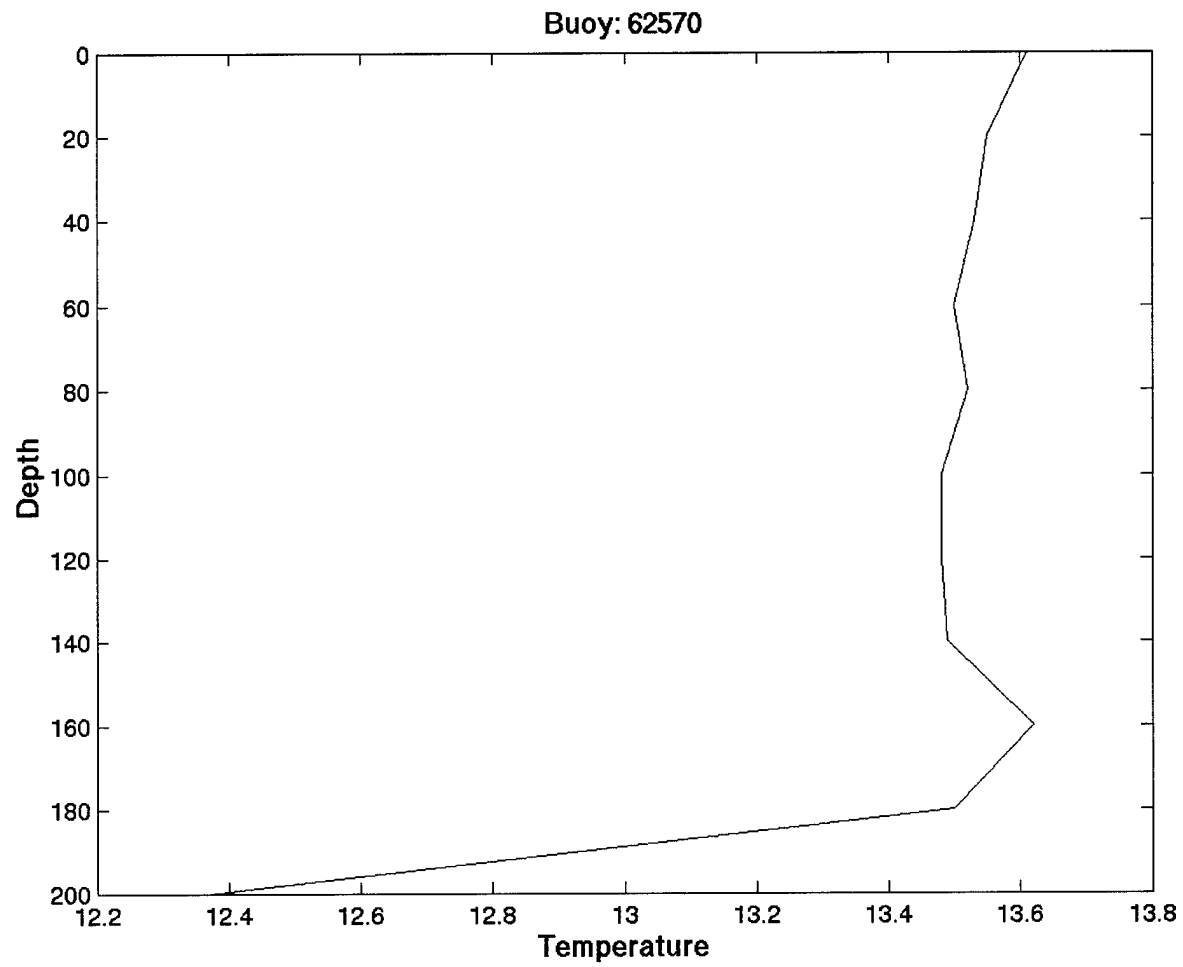Figure 16.   GODAE Floats in the Eastern North Atlantic.

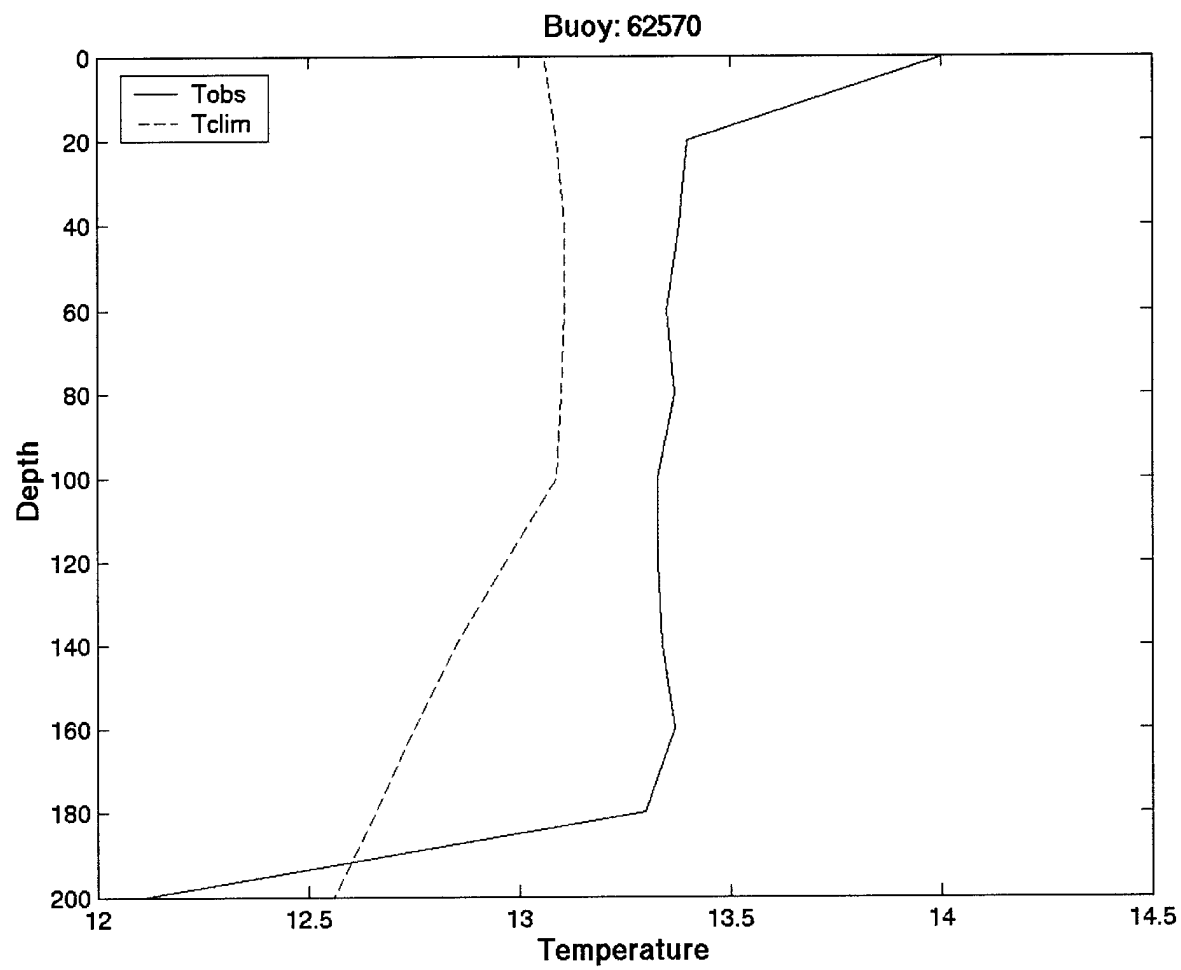Figure 17.   Temperature vs. Depth.

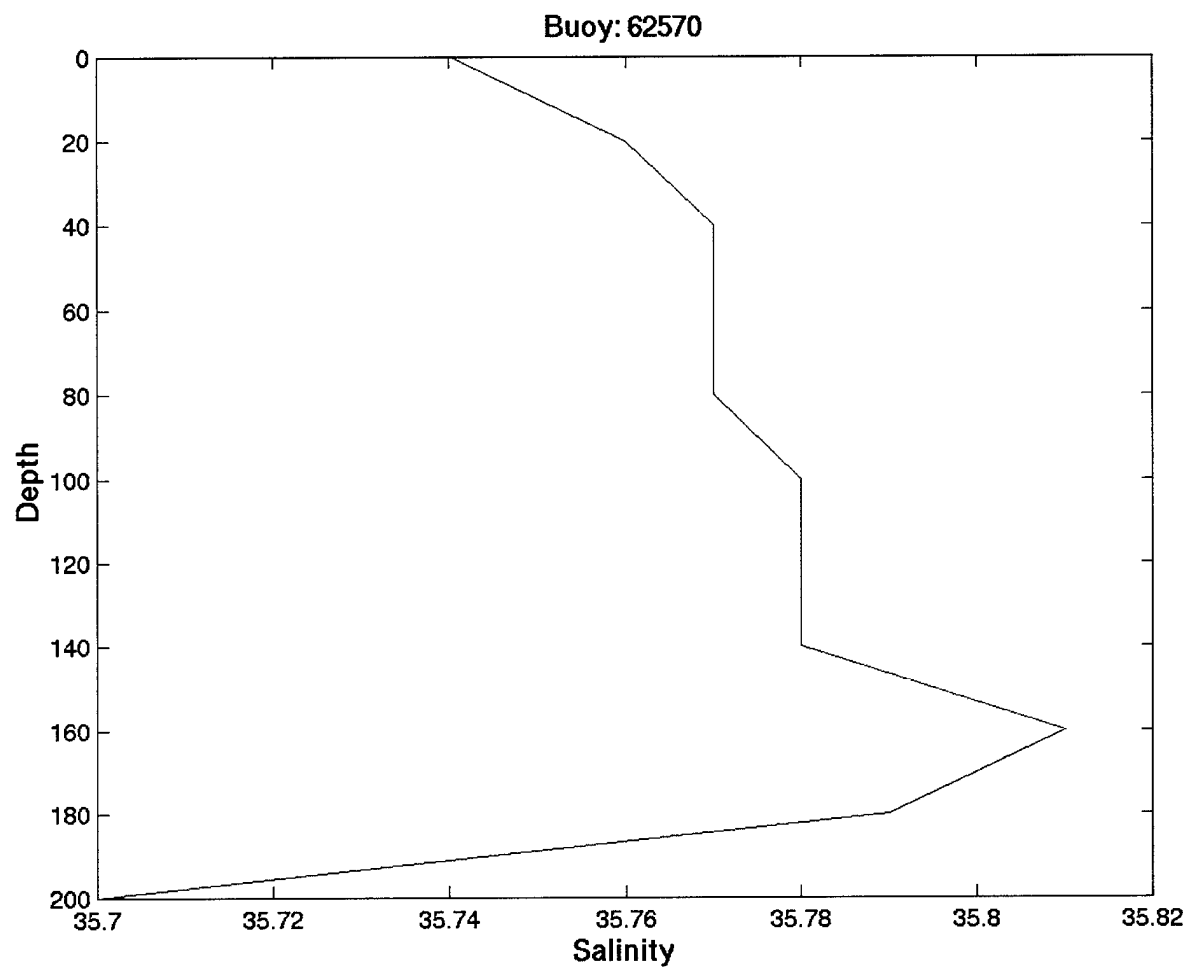Figure 18.   Temperature Observed vs. Temperature Climatology.
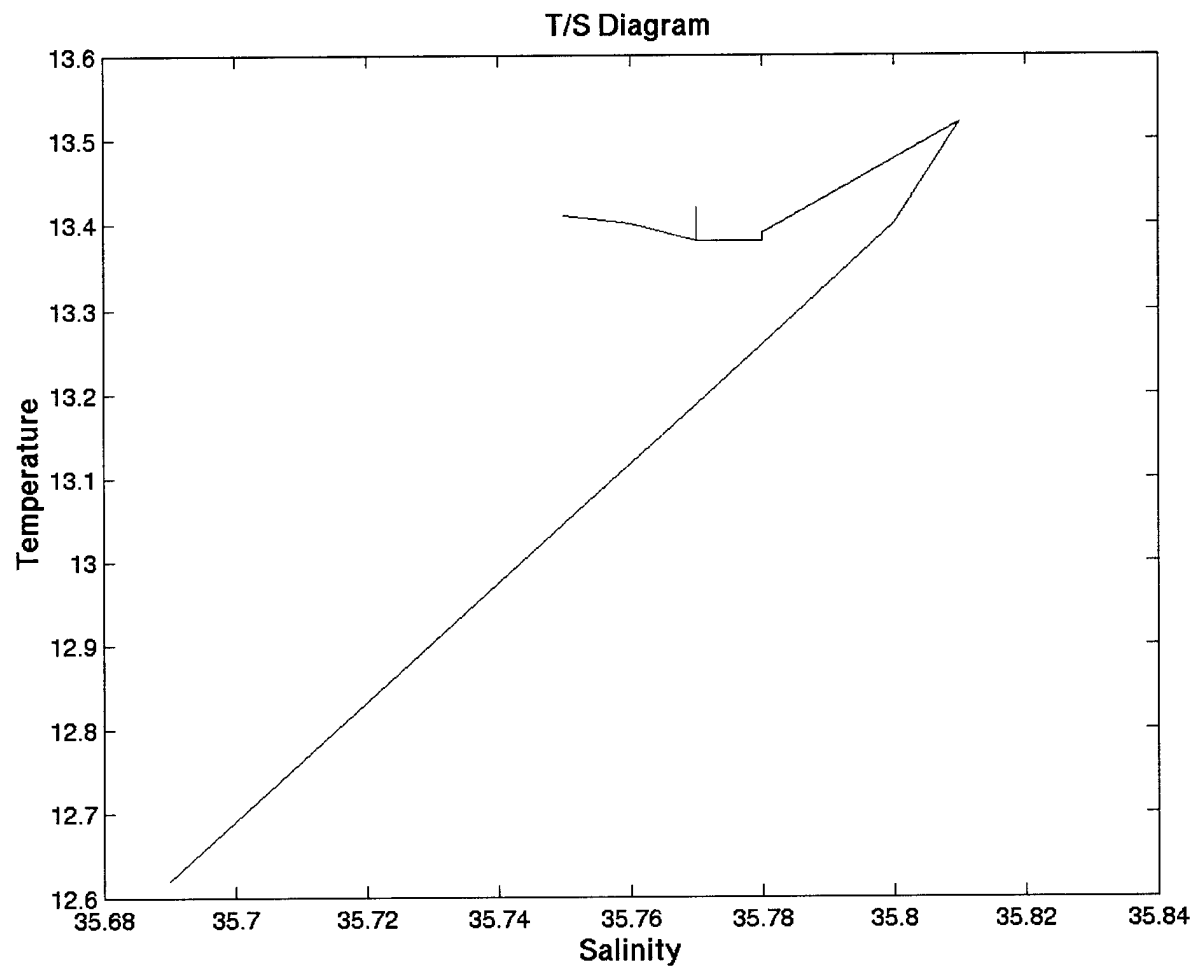
Figure 19.   Salinity vs. Depth.

Figure 20.　　Salinity vs. Temperature.

Data Type Code	PROFILE DATA TYPE	Data Type Code	PROFILE DATA TYPE
0	All Data Combined	21	Ship Bucket
1	Expendable BT	22	Ship Hull Sensor
2	NOAA 14 Day MCSST	23	CMAN SST
3	Ship Engine Room Intake	24	NOAA 15 Day MCSST
4	Fixed Buoy	25	NOAA 15 Night MCSST
5	Drifting Buoy	26	NOAA 15 Relaxed Day MCSST
6	NOAA 14 Night MCSST	27	Mechanical BT
7	NOAA 14 Relaxed Day MCSST	28	Hydrocast BT
8	SSM/I F11 Ice	29	SSM/I F15 Ice
9	SSM/I F13 Ice	30	*In Situ* SSH
10	SSM/I F14 Ice	31	SSM/I Ice Shelf
11	ECMWF Climate	32	TESAC Salinity
12	TOPEX Sea Surface Height	33	MODAS Salinity
13	ERS2 Sea Surface Height	34	TRACK OB Temperature
14	GFO Sea Surface Height	35	TRACK OB Salinity
15	MODAS Temperature	36	PALACE Float Temperature
16	NCEP SST Climate	37	PALACE Float Salinity
17	GOES 9 Day SST	38	MODAS Supplemental far-field temperature
18	GOES 9 Night SST	39	MODAS Supplemental far-field Salinity
19	GOES 9 Relaxed Day SST	40	Supplemental SSH Anomaly
20	TESAC Temperature	41	Supplemental Sea ICE SST

Table 1.   Profile Data Types Available on the USGODAE Server (UST, 1999).

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13.   Wilson, Stan. *"Launching the Argo Armada."* Oceanus. Vol. 42. No. 1. pp. 17-19. 2000.

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